SHORT LECTURES

TO

ELECTRICAL ARTISANS.

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BEING A

COURSE OF EXPERIMENTAL LECTURES DELIVERED
TO A PRACTICAL AUDIENCE.

BY

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PREFACE.

These short Lectures require a word, by way of preface, to explain that they were not in any way intended as a connected exposition of even elementary principles of electro-technics. Being desirous that practical training should be supplemented by some attention to theory, Mr. R. E. B. Crompton requested me to give during the past winter some Lectures on subjects connected with the principles underlying modern electrical engineering to the pupils and workmen associated with his firm, and the following pages contain the transcript of these Lectures delivered at Chelmsford. Confident that the right direction for technical training is to bring home to the craftsman the scientific principles involved in daily work which passes under his hands, the subjects which most naturally claimed attention were those involved in everyday experience of the audience addressed. It is with the hope that the elementary explanations here given may be useful to other similar practical students, and as introductory to larger treatises, that they are here reprinted.

J. A. F.

September, 1886.

PREFACE

TO THE SECOND EDITION.

THE call for a second edition has afforded the opportunity to erase several typographical errors, and to remove some other blemishes which had escaped notice and correction in the first edition of this little book, but which courteous critics in the technical journals have pointed out. It has not been deemed desirable to enlarge the scope of these elementary expositions, since to do this effectually would have altered the character of the book. At the same time many paragraphs have been re-worded, in the hope that clearness might thereby be gained.

J. A. F.

UNIVERSITY COLLEGE, LONDON.
January, 1888.

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SHORT LECTURES

TO

ELECTRICAL ARTISANS.

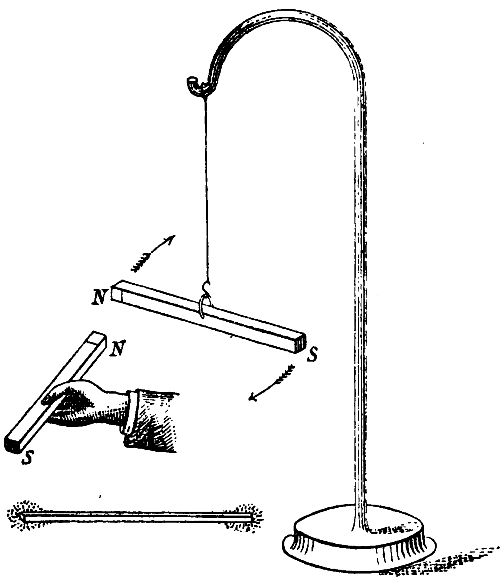
LECTURE I.

§ 1. I HOLD in my hand a large fragment of a certain iron ore, found in various parts of the world. It is a combination of iron and oxygen, similar in nature to, but not exactly the same as the rust or scale which forms on iron which has been exposed to the fire. This native oxide of iron has however two properties not possessed by a fragment of ordinary iron scale. If it is placed in iron filings, these are attracted to it and stick to it, adhering mostly at two points on nearly opposite sides; also if a properly-shaped fragment is hung up by a fine silk thread, it will take up a definite position with respect to the north and south direction. This iron ore is called a lodestone, or *natural magnet.* These properties of it were known from very early times, both to the Greeks and to the Chinese. If we take a steel knitting-needle and stroke it always one way with that corner of a lodestone which most attracts iron filings it is found that the lodestone imparts its peculiar property to the steel, and the steel needle then possesses the power of picking up filings by its ends, and of turning round to point nearly

north and south, when balanced horizontally upon a cork floated on water. A steel bar so treated is called a *permanent* or *artificial magnet.* Steel is a compound of iron and carbon, called a carbide of iron. If in place of the steel knitting-needle we try to magnetise a *short* length of soft or pure iron wire, well annealed, we shall not succeed in giving it permanent magnetism, like the steel, but it will acquire the properties of the lodestone, as long as it is in contact with it. Lodestone is difficult to procure, but these experiments may be repeated by using instead a small steel horse-shoe magnet, purchased of any ironmonger. To this should be added some steel wires or knitting-needles, a few lengths of very soft iron wire, some skeins of floss silk, and some iron filings in a muslin bag. Provided with this simple apparatus we begin to interrogate nature by experiment. Stroke a steel needle, about three inches long, with one end of the horseshoe magnet, always rubbing one way, *not* backwards and forwards. Suspend this magnetic needle by a length of unspun silk, tied to its middle, and support it by any convenient stand. (See Fig. 1.) We see that after a few swings it settles down in a certain direction. This direction is called the *magnetic meridian* at that place. Now magnetise a second steel needle, about six inches long, and roll it in the iron filings. Note that the filings will only stick on at the extreme ends, but not in the middle. The ends of a magnet at which it exhibits its powers are called the *poles.* (See Fig. 1.) Present this last needle to the suspended needle, called henceforth the *test-needle,* we find that the one pole of it attracts one pole of the test-needle and repels the other. Mark the end of the test-needle, which points towards the north, when no magnets are near it, with a bit of red paper or paint. Call this the *red pole* or north pole. Mark the other end blue. Make a second test-needle, magnetise it, mark it in the same way, and try how its poles affect those of the first. You will find red pole attracts blue pole, but red pole repels red pole,

and blue pole repels blue pole. Store up in your memory the following rule for future use. *Like poles repel—unlike poles attract;* that is, poles of the same name, or colour repel; but attract the opposite kind.

Fig. 1.

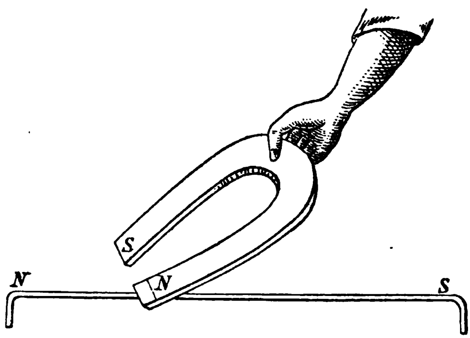


Repulsion of similar Magnetic Poles.

Proceed now to stroke with your horse-shoe magnet a short length of soft iron wire, which has been carefully annealed by heating red hot, and letting it cool very slowly. It will be found that it does not acquire magnetic properties to anything like the same extent as the steel: but it does acquire feeble poles at the ends, and will attract and repel the ends of the test-needle. If, however, we give this iron wire a knock, or better, a twist, its magnetism all disappears,

and, moreover, such magnetism as it can acquire by stroking with the horse-shoe magnet will nearly all disappear if the iron wire is heated to a red heat. That quantity of magnetism which the iron will retain, provided always it is not shaken or twisted, is called the *residual* magnetism. The effect of torsion in getting rid of residual magnetism in iron is best shown by taking a soft iron wire, about No. 16 B.W.G., a foot long, and turning up half-an-inch at each end, the better to twist it by. (See Fig. 2.) Stroke this

Fig. 2.



Temporary Magnetisation of Soft Iron.

wire gently with one pole of a strong horse-shoe magnet, and then test its ends by iron filings, or the *test-needle;* it will be found to be magnetic to a certain degree. Holding it by the turned up ends, give it half a dozen twists—first right, then left. All magnetism will then have disappeared from the wire. Soft or pure iron differs therefore from steel, in that, whilst capable of being magnetised by a magnet, it cannot retain magnetic polarity with the same degree of permanency as steel. Steel magnets can be deprived of their magnetism by strong blows and twists, but magnetised iron holds its magnetism less strongly than magnetised steel. As a

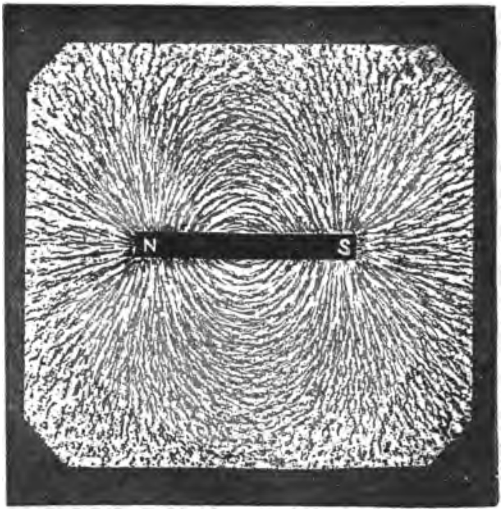
practical precaution, steel magnets should be handled carefully, and not knocked or allowed to fall. In addition to iron, it is found that two other metals, cobalt and nickel, are capable of being strongly attracted by a magnet. Small pieces of these metals may be procured at the wholesale chemists, and it will be found that a small horse-shoe magnet picks them up readily, but does not impart to them permanent magnetism. A curious fact has been brought to light quite lately with reference to steel containing manganese. An alloy of steel, with 12 per cent. of manganese,* is almost unaffected by a magnet, and cannot be attracted by it. This manganese steel is very hard. Faraday made the discovery that all bodies are slightly affected by a powerful magnet. Bodies which are attracted by a magnetic pole are called *para-magnetic*, or simply magnetic bodies. Substances which are repelled by a magnetic pole are called *dia-magnetic*. The best representative of the latter class is the metal bismuth, but it should be understood that the property of being repelled by a magnet is only manifested to a very feeble extent, even by bismuth, and cannot be detected except by the use of very powerful magnets. Hard steel stands out conspicuously amongst magnetic bodies in respect to its retentiveness for magnetic polarity.

§ 2. The space all round or near a magnet in which its influence is felt, is called the *magnetic field* of that magnet. Take a large bar magnet and place it on a table, and proceed to hold a small magnetic test needle in various positions near it. It will be found that the test-needle takes up different positions at every point in the neighbourhood of the large magnet. The direction in which a pocket compass needle or small test-needle points when held in a magnetic field is called the *direction of the field* at that point. Let us take a steel bar magnet, which may be conveniently about twelve inches long, one inch wide, and one-eighth inch

* This manganese steel is prepared by Messrs. Hadfield, Sheffield.

thick; lay this on a table and place over it a large sheet of thin cardboard. By means of a muslin bag filled with steel filings, sprinkle steel filings lightly and very uniformly over the card. Then tap the card very gently. The steel filings will arrange themselves in beautiful curves, see Fig. 3.

Fig. 3.

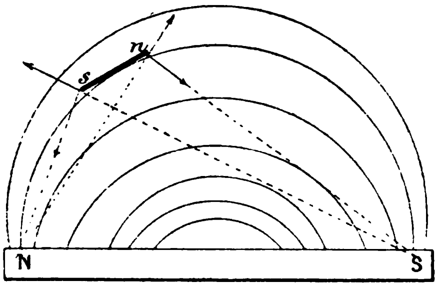


Lines of Force of Bar Magnet delineated by Steel Filings.

Instead of using a bar magnet we may employ a horseshoe magnet, and obtain other forms. Provide a little test-needle, made by magnetising a sewing-needle and suspending it at its centre by six inches of silk fibre, and hold this test-needle close over the card so that the test-needle vibrates horizontally, but without touching the card or the filings. (See Fig. 4.) We shall find that the test-needle at any place always sets itself *along* the direction of the

curves marked out by the steel filings. These curves therefore show the direction of the field, or of the magnetic force at every point, and are called *lines of magnetic force.* We define them by saying that a line of force is a line so drawn that at any point its direction is the same as that of a small

Fig. 4.



Test-needle *n s* held in Field of Bar Magnet.

compass-needle held at that point. In order to render these magnetic figures or curves permanent, and to study their various forms, we may proceed as follows:—Engineers use a kind of photographic paper for copying tracings, called Ferro-prussiate paper.* When this is exposed to sunlight it turns grey-green, and when afterwards washed with water, the part so exposed to the light turns blue. On a frame of wood we strain a sheet of this paper, and place the frame and paper over a magnet or magnets laid on a table. On the chemical paper we then sprinkle steel filings as before, and obtain the magnetic curves. The frame is then to be gently lifted off away from the magnets, taking care not to disturb the lines, and placed in the sunshine. In a short time the paper turns a dark grey-green at all

* It can be procured of Mr. Stanley, mathematical instrument maker, Great Turnstile, Holborn, London.

points where it is not defended from the light by the filings, and the filings are then removed and the paper washed with water. The picture develops, showing the lines of force marked out beautifully in white lines on a blue ground. By this simple means permanent diagrams of different forms of the magnetic curves may be obtained for different magnetic fields, and the study of the forms of these various fields is highly important to practical electricians. In looking at these magnetic diagrams, it will be noticed that near the poles of the magnet the lines of force are very much thickened up by the crowding together of the steel filings, but that further away the lines are thinner and less well marked. Close by the magnet, where its magnetic force is greatest, the magnetic field is said to be *strong*, but away from it it is said to be *weak*.

§ 3. In order to define these terms more strictly, we must refer to the mode of measuring forces adopted in scientific work. Generally speaking we measure a force by comparing it with the weight of one pound avoirdupois. We thus speak of a pressure of steam of ten pounds on the square inch, meaning a force or pressure on the square inch equal to the force required to support a weight of ten pounds. But since the force required to support a piece of metal called a weight of one pound, is different at different parts of the earth, and dependent on the latitude of the place of experiment, this method is not scientific and requires modification. We take as a standard of mass a piece of metal called *one gramme;* 453·59 grammes are equal in mass to one pound avoirdupois. We take as our standard of length *one centimetre;* 2·5 centimetres make one inch nearly. These are called metric or French units. They are universally adopted as scientific units of mass and length.

Suppose the gramme falls under the action of gravity at Paris, and we observe the velocity it has obtained at

the end of one second. It is 981 centimetres per second nearly. It is agreed that *a force* shall be measured by the velocity it can impart to a mass of one gramme after acting upon it for one second. Accordingly a unit of force is a force which can impart a velocity of one centimetre per second to a mass of one gramme after acting upon it for one second. This unit of force is called *one dyne*, and the force of gravity at Paris 981 dynes. A force of one million dynes is called a *megadyne*, and the weight of 2¼lbs. at London is about a megadyne. Let us apply these methods to magnetic measurements. If we magnetise a long knitting-needle, we shall, as above stated, find magnetic poles at the ends, but no power at all in the middle. Break the magnetised needle in the middle, two new poles of exactly equal strength appear at the broken ends. Imagine these poles placed one centimetre apart, and the attraction between them measured by a very delicate balance. If these two poles so placed attract each other with a force of one dyne, they are said to be *unit poles*. The square root of the number which expresses the attraction in *dynes* between two equal magnetic poles placed one centimetre apart is a measure of the strength of each pole.

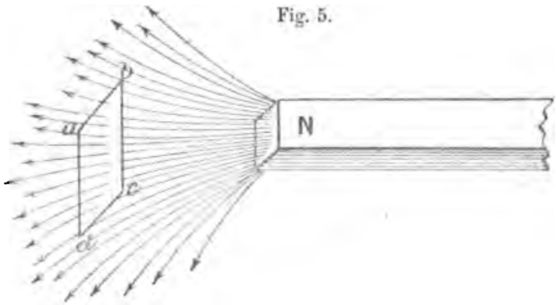
§ 4. If a unit magnetic pole is held at any point in the field of another magnet, and the force of the field on this unit pole measured in dynes, then this number is a measure of the strength of the field at that point. Imagine a long magnetic needle, having a pole of unit strength, held in the field of a bar magnet, and we find the force on the unit pole to be ten dynes, then the field has a strength of ten at the point where the unit pole is placed.* We have thus a definition of what we mean by the *strength of a magnetic*

* The testing magnet must be *long*, so that the other pole of it may be removed far out of the way, and not interfere with the result. If a "pull" is measured in grammes weight, then to convert to *dynes* we must multiply by 981.

field. It is the force acting on a unit magnetic pole placed in that field. We may thus with a unit magnetic pole explore a field and note at each point its strength, and by means of a small testing-needle determine its direction at every point. A *uniform field* is a field whose strength is the same at every point.

It is possible to make use of lines of force to show not only the direction but the strength of the field at every point. To do this, proceed as follows: Consider the lines of magnetic force branching out from a magnetic pole.* At any place hold a little square frame perpendicular to the lines of force, of area equal to one square centimetre (see Fig. 5), and imagine that over the area of the frame so

Fig. 5.



Lines of Magnetic Force traversing an Area *a b c d.*

placed at any point in the field, we measure as above the strength of the field. Then let the lines of force be so spaced out that the number passing perpendicularly through this frame is equal to the average strength of the field over its area. It is obvious that where the field is strong, the lines of force are closely packed, and where it is weak, they

* Our delineation of lines of force by steel filings gives us only the lines of force in one plane. It must be remembered, however, that from the pole of a magnet lines branch off in *every* direction.

are far apart, and their density or compactness is everywhere a measure of the strength of the field. If the strength of the field or the force on a unit pole is ten dynes at any point, then ten lines of force must pass through a little area of one square centimetre held perpendicularly to those lines.

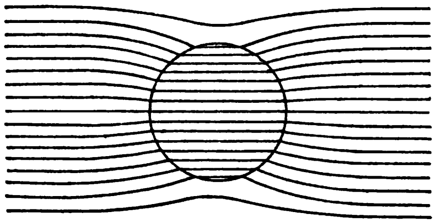
In all our reasonings and discussions about magnets hereafter, we must carry in our minds a clear conception of a magnet so surrounded by its lines of force spaced out according to this rule. The system of lines of force, so to speak, forms part of the magnet, and moves with it rigidly whereever it goes. We have already defined above what we mean by a unit magnetic pole or pole of unit strength. We can now define the strength of the pole of any magnet as the number of unit poles which must be put together to be equivalent to it in strength.

§ 5. A very important magnetic quantity is the number obtained by multiplying together the strength of a magnet's pole and the magnetic length of the magnet. This product is called the *moment* of the magnet. In the case of steel bar magnets of ordinary length, the poles are not strictly at the extremities, hence the *magnetic length* is a little less than the actual length of the magnet. For most bar magnets the magnetic length is about ·83 of the end to end length. If the magnet is not straight, but, say, horse-shoe shaped, the *magnetic length* is the *shortest* distance between the poles. The moment of a magnet divided by its volume, gives us a number which expresses the average *intensity of magnetisation* of that magnet, or simply its *magnetisation.* Adopting the centimetre gramme and second units, the greatest magnetisation possible for soft iron is from 1400 to 1700 units; whilst the maximum magnetisation possible for hard steel is 300 to 600. The average magnetisation of the earth considered as a magnet is, according to Gauss, about ·08 of a unit in C.G.S. measure (see Lecture V.).

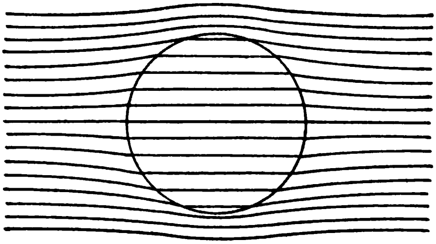
§ 6. If in a uniform field of magnetic force we place a

sphere of soft iron, the result found on delineating the lines of force is to show that the iron concentrates and collects the lines of force, or that it causes them to crowd together so as to pass through the iron in greater number than they

Fig. 6.



Lines of Force of Paramagnetic Sphere in uniform Magnetic Field.



Lines of Force of Diamagnetic Sphere in uniform Magnetic Field.

would do through the same space if the iron were not there. (See Fig. 6.) Supposing, however, that a sphere of very powerful diamagnetic substance, such as bismuth, is placed in similar circumstances, it has an opposite effect upon the field, causing a divergence of the lines.* Magnetic bodies

* The iron may be said to have *convergivity* for lines of magnetic force, just as a convex lens has for light, and bismuth or a diamagnetic may be said to have *divergivity* for lines of magnetic force, just as a concave lens has for rays of light.

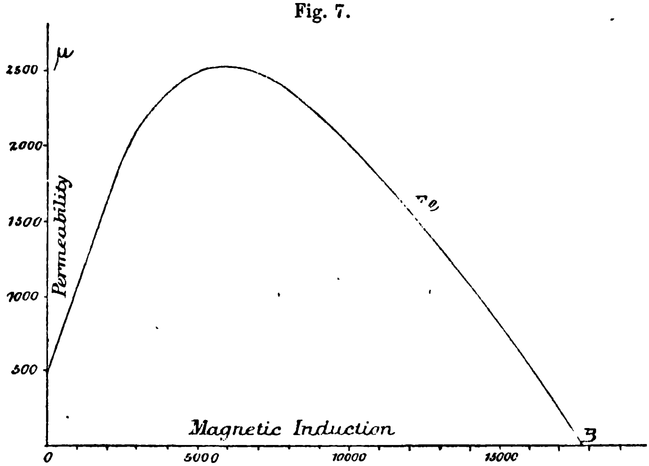
then concentrate lines of force on to themselves, and diamagnetic ones shed them off. It appears as if the lines of force found a more easy passage through the iron than through the air, and on account of this behaviour the iron is said to have greater *permeability* than air, or greater conductibility for lines of force or less *magnetic resistance*. The passage of the lines of force of the uniform field through the iron magnetises it and develops poles in the iron at the places where the lines of force enter and where they leave it. These poles are called *poles of induction*, and the soft iron is said to acquire magnetism by induction whilst it is in the field. Suppose that a very thin bar of iron is placed in a uniform field along the lines of force. It is magnetised by induction whilst *in* the field, and it exhibits all the properties of a magnet. The intensity of its induced magnetisation, divided by the strength of the field, is called its *magnetic susceptibility*. This quantity is denoted by the letter k, and k therefore, measures the magnetisation of a thin bar when placed in a field of unit strength. Let us suppose this long thin bar of iron to have a cross section of one unit or one square centimetre, and that the bar is at least a hundred times as long as it is wide. Let such a bar be placed in a field of unit strength. Then lines of force are concentrated through it, and more lines of force go through it than would pass through the same space if it were not there. The number of lines of force passing through one square centimetre of cross section of the iron is called the *magnetic induction*, or simply the *induction* through the iron. The ratio of the induction through the iron to the strength of the original field, or to the number of lines of force which would pass through the space occupied by the iron if it were not there, is called the permeability of the iron, and is denoted by the letter μ.

We have then two relations:—

Intensity of magnetism = susceptibility × field strength,
Induction = permeability × field strength,

for determining the magnetisation and the number of lines of force respectively passing through a long bar of iron placed along the lines of a magnetic field and magnetised by induction. If the permeability and susceptibility were constant quantities for various kinds of iron and steel, we should be able to calculate, by a simple multiplication, the magnetisation or induction through a long bar placed in a field. It has been found, however, that if a very small number of lines of force are passing through iron then the permeability has a value which is less than when a larger number pass; but the permeability does not increase continually. It rises to a maximum and then falls, and for a certain high value of the induction the permeability is very small. Physically what this means is, that the first effect of

Fig. 7.



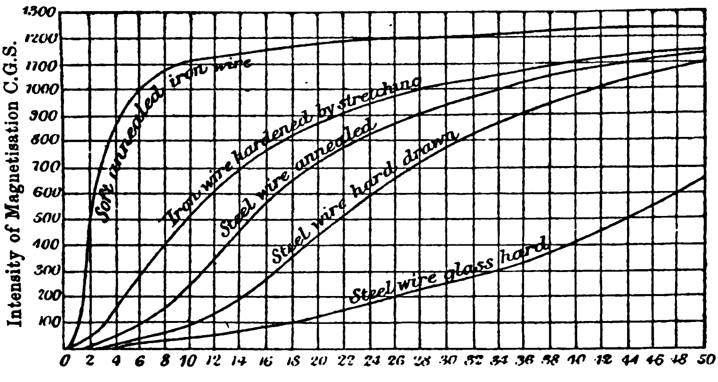
Curve showing the relation of Magnetic Permeability to Magnetic Induction in C.G.S. units in the case of Soft Iron. (Rowland.)

passing lines of force through iron is to make it more easy to put a few more; but as more and more are put in, the

capacity of the iron to hold lines of force becomes less and less, and finally it refuses to allow any more to pass. The curve in Fig. 7 shows the rise and subsequent fall in permeability of iron. (See Appendix I., p. 203.)

§ 7. Supposing a bar of iron to be placed in a magnetic field of gradually increasing strength and corresponding to every particular value of field, we measure the intensity of its induced magnetisation, and that also the same experiment is performed with steel bars, we shall observe the following facts.—As the magnetising field increases, the magnetisation at first increases, but finally becomes stationary. If we plot down these values of magnetisation and field we get what are called curves of magnetisation. (See Fig. 8.) The point at

Fig. 8.



Curves of Magnetisation for Iron and Steel. (Ewing.)

which the iron refuses to be further magnetised by any force, is commonly called the point of *saturation*. The curves show that for a given field iron is capable of greater magnetisation than hard steel. We find, however, one great

difference between iron and steel. When the magnetising force is removed the steel retains as permanent magnetism a great proportion of the induced magnetism, and it will retain it, even if handled or laid aside. The iron also retains, when removed from the field, a very large proportion, perhaps some 90 per cent. of its induced magnetism, provided that it is not shaken or twisted in the least degree; but any shock or twist deprives it at once of this large proportion of magnetism, and only leaves in it a very small, residual amount called the *residual magnetism.*

§ 8. During the application of the magnetising force, any blows or shaking tend to facilitate the acquirement of magnetism, but when removed from the field, the same causes tend to remove it. Heat operates in the same way. If a piece of steel is made red hot, then placed in a strong magnetic field and suddenly cooled, it acquires very strong permanent magnetism.

Iron at a bright red heat is, however, not affected by a magnet. Its susceptibility is zero.* The moment of a steel magnet is diminished by heat, and is said also to be diminished by extreme cold.

One very plausible supposition to make in order to account for these facts, is to assume, as we are justified in doing, that every little molecule or particle of iron is already a magnet and possesses its two poles. The process of magnetising consists in arranging all these particles with their poles in similar directions.

If a glass tube about twelve inches long and half-an-inch in diameter is filled with *steel filings*, and then closed at

* The most simple way to regard the "susceptibility" and "permeability" of iron or steel is to consider these quantities as numbers, by which we must multiply the magnetising field in order to obtain the intensity of magnetisation and number of lines of force per square centimetre through the iron respectively, provided this be in the form of a long thin bar placed along the lines of force of the field.

each end with a cork, such a tube of steel filings can be magnetised by a strong magnet, and will be found to preserve permanent magnetism. It will attract and repel by its ends our test-magnet, and will itself set north and south if suspended. Now loosen one of the corks and shake the tube, every little steel filing is re-arranged. Each still retains its magnetism, but the indiscriminate or any-how arrangement of the particles, causes their actions to neutralize one another, and hence we find after shaking and closing up again, that our tube has lost all its previous magnetic polarity. If by any magic process we could restore all these little irregularly arranged magnetic particles of steel to their original positions, we should again find the tube as a whole to be magnetic. The theory proposed to account for the magnetisation of iron is as follows:—Each little particle of iron is supposed to be, and to remain always magnetic. In an unmagnetised iron bar, these molecular magnets are arranged irregularly. These little molecules resist being turned out of their usual positions. Hence when a magnetising force is brought to bear upon them, the first effect is to turn those little molecules round, whose axes are already most nearly in the direction of the magnetising field. As the magnetising force increases others are turned, increasing thereby the apparent magnetism; at last, all are turned with their poles in the direction of the magnetising field. When this is the case, no further application of magnetising force, however great, can increase magnetisation. This is the point of saturation. It is easily seen that shocks, or heating, or anything which loosens the molecules tends to facilitate the acquirement of magnetisation. On removing the magnetising force, those molecules which have not been much strained out of their position, fall back to their old directions; but those which have been greatly strained have acquired a permanent *magnetic set* and hence remain. In the case of torsion of a wire, we have a similar

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behaviour. A slight torsion within the limits of elasticity disappears when the twisting force is removed, but a violent torsion results in a permanent deformation, which does not disappear when the twisting force is removed. This magnetic *set* produces the residual magnetism.

This theory explains how iron can remain, as it were, super-charged or super-saturated with temporary magnetism. In the iron there is very little resistance to magnetisation, that is to say, the molecules do not resist very strongly being turned in similar magnetic directions, and hence when the force is removed, there is very little restoring tendency to make them go back into irregular positions, but a little knock or twist imparts just the necessary disturbance, and causes the regularity of arrangement to disappear, and with it the apparent magnetism.

From experiment, it appears that the greatest number of lines of force which can traverse a long bar of soft annealed iron one square centimetre in cross section, is about 32,000 in C.G.S. units. For cobalt and nickel the maximum values are 10,000 and 6,000 respectively. These inductions bestow on these metals a maximum magnetisation of 1,700 C.G.S. units for iron, 800 for cobalt, and 500 for nickel. Cast steel appears to be from 300 to 600.*

§ 9. We have noted above that iron is capable, when gently treated, of retaining a very large percentage of magnetism in a supersaturated state. If the experiment is tried with a short, squat piece of iron, it will not be found to retain much residual magnetism after removal from a magnetising field. This is because the poles at the end exert a de-magnetising action. In the case of long bars, the poles are so far removed from the middle that this is not the case. Hence, as a practical precaution, if soft iron electro-magnets are required to de-magnetise quickly, the cores should be short and thick, and not long and thin.

* For the most recent information on this subject see Appendix I.

In making good permanent steel magnets, what is required is very uniform or homogeneous cast steel; the bar must be uniformly tempered, and fine in grain. Preference is given to glass-hard tempered English cast steel.

In making the cores of electro-magnets, the proper material is the best Norway or Swedish iron very uniformly annealed. The iron should be heated for some time at a cherry-red heat, and then very slowly allowed to cool by being buried in sand. If the iron is required to be very soft, it must not be touched with tools after annealing.

LECTURE II.

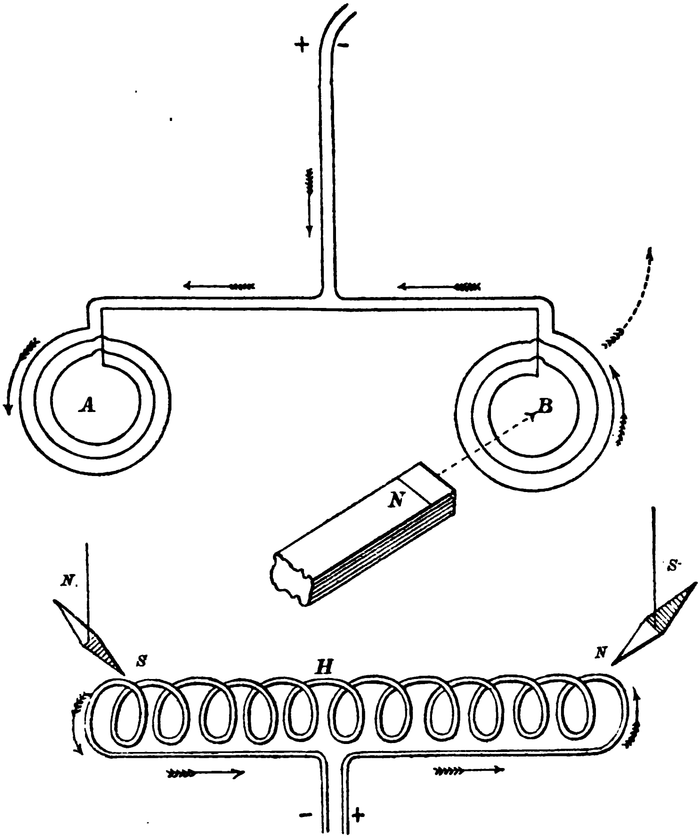
§ 10. In 1820, Oersted made the capital discovery that when an electric current is passed along a wire it magnetises that wire, no matter of what material it is made, and creates around it a magnetic field. This proved to be a very fertile discovery, and Arago completed it by showing that if a wire is bent into a circle and a current of electricity sent through it, such a circular current has exactly the same magnetic qualities as a round disk of steel magnetised perpendicularly to its surface. The magnetic effect of one single turn of a circular current is, however, feeble. Let us take a great length of covered wire and wind it up so as to make two flat circular coils. If these coils are freely suspended by thin leading wires twisted together (see Fig. 9), and a strong current sent through them, then we find that such a circular current is highly magnetic, and if a strong magnet is presented to it, it is either attracted or repelled, according to the nature of the pole and the direction of the current in the coil.

If instead of winding the wire into a flat coil it is wound into a helix, as at H (Fig. 9), this helix when traversed by a current, becomes magnetic, and if tested by a little test-needle, we find one end exhibits north polarity, and the other south. It is important to obtain a clear conception of the nature of the magnetic field around and within a circular coil of wire carrying a current. By testing it in different places with a little test magnetic needle, it is easy to demonstrate that the nature of the field is as shown in Fig. 10.

Let us place the circular coil before us, so that the current

appears to go round it in the opposite direction to the movement of the hands of a watch. This is called the positive

Fig. 9.

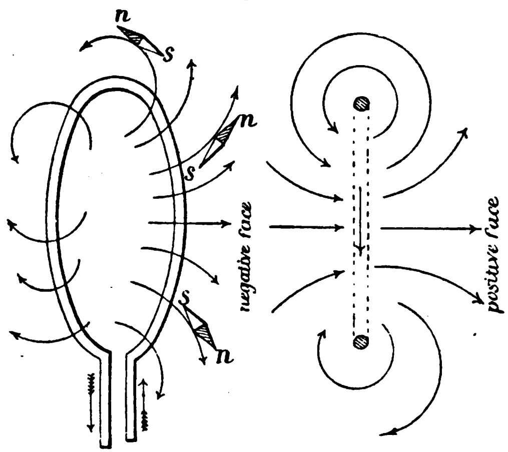


Magnetic Qualities of a Conductor conveying an Electric Current.

direction. The lines of force come out towards us from the aperture of the coil nearest to us, and spread out and return

back over the wire into the opposite face of the aperture. Bear in mind that the direction of the lines of force is found at any spot by holding a small magnetic test-needle at that point and noting the direction in which it sets, and the direction of its marked or north pole.

Fig. 10.

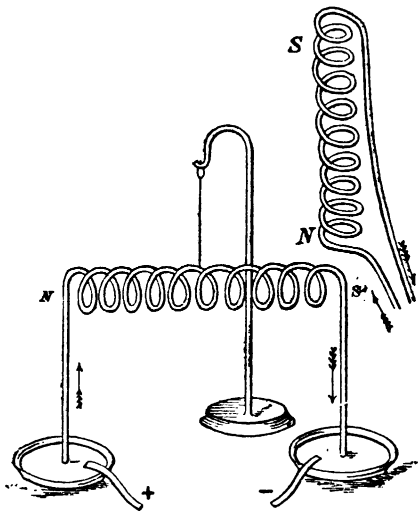


Magnetic Field of Circular Current.

For a long closely wound spiral conveying a current the lines of force are similar to those of a bar-magnet of the same cylindrical form. These lines of force must be thought of as closed loops linked with the current. The conductor conveying the current passes through all the loops of force, and these are, so to speak, threaded or slung on the current line, or line of flow. It will be readily inferred that since a solenoid of wire conveying a current attracts and repels by its extremities the poles of a magnet, two such spiral conductors conveying currents should attract and repel each other. This is found to be the case. Make a

helix, by winding covered wire, say 100 feet of No. 16 wire, on a cardboard tube an inch in diameter and seven or eight inches long. (See Fig. 11.) Suspend it by a thread from its centre and let the ends of the wire hang down and just touch the surface of mercury in two saucers. In this way it is possible to send a current of electricity from a few cells of

Fig. 11.

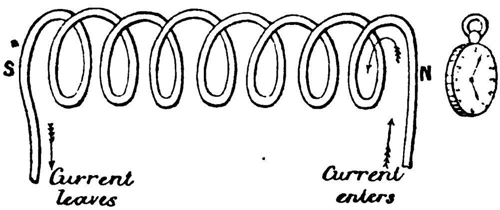


Attraction and Repulsion of Spiral Currents.

primary or secondary battery through the spiral, and yet leave it free to move. On presenting to such a freely suspended helix, or spiral conductor, another similar spiral, also traversed by a current, we shall find that these two screw-like currents just behave to one another as if they were magnets; and their similar poles repel, and unlike, or opposite poles, attract. We must then consider every circular current as if it were a very short magnet, the one

face of the circle being the north end, and the other face the south end. If we place the circular current before us, so that the current appears to revolve in the contrary direction to the hands of a watch, then the face nearest to us is the north-seeking pole. (See Fig. 12.)

Fig. 12.



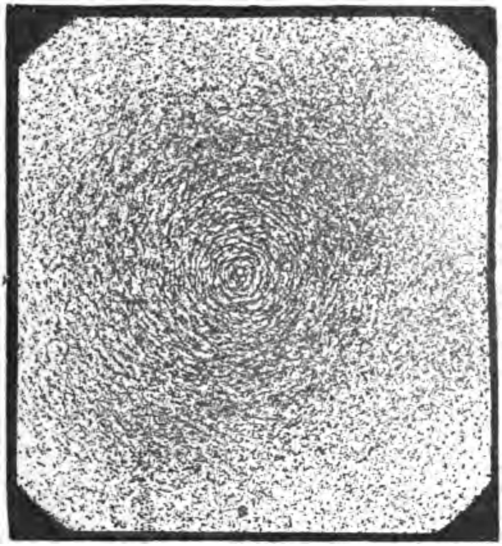
Poles of a Solenoid.

§ 11. It is essential to have a clear conception of the nature of the magnetic field round a straight wire conveying a current. We determine this by the following experiment:—Pass a straight wire up through a hole in a piece of cardboard, and sprinkle the card uniformly with steel filings. Send a very strong current through the wire, using say, a No. 10 B.W.G. wire and 50 ampères of current. Tap the card. The filings arrange themselves in a beautiful series of circles. (See Fig. 13.) Hold the little test-needle above the card. Everywhere we find the test-needle places itself at right angles to the radii of these circles, or in other words, stands tangent to the lines of force. We must make a mental representation of the nature of the field round a straight current as follows:—The lines of force are concentric circles whose planes are perpendicular to the direction of the wire. (See Fig. 14.) The direction of these lines of force is related to the direction of the current in the following manner: let us suppose a watch strung on the wire so that the current goes in at its face and comes out at

its back, then the direction of the lines of force is in the direction in which the hands rotate.

§ 12. Provided with these notions of the magnetic field of a current, I now wish to help you to explore a region of facts, the first entry into which was made by Faraday, in the

Fig. 13.

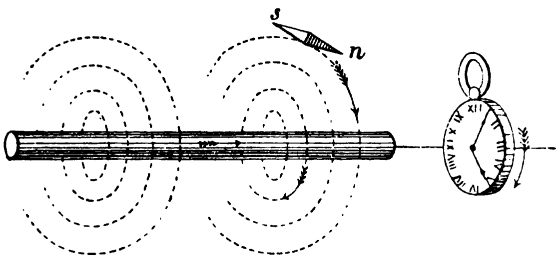


Circular Lines of Magnetic Force surrounding a No. 16 Wire conveying an Electric Current of 30 ampères, taken in a plane perpendicular to the wire.

autumn of the year 1831. In order that you may actually see these effects, and not simply hear about them, it has been necessary to devise a simple arrangement for rendering apparent the existence or presence of an electric current in a wire. From what we have already seen, you will infer that a small magnetic needle, hung in the centre of a circular coil

of wire, will, when that coil is traversed by a current, tend to place itself perpendicular to the plane of the coils, or to stand along the axis of the coil. On a brass bobbin is wound a few dozen yards of thick cotton-covered wire. Within this bobbin is hung a little circular mirror *m* of silvered microscopic glass; to the back of this mirror are attached, by shellac varnish, three or four little magnets of watch spring. The mirror may be half-an-inch in diameter or so. Its suspension is a short length of the finest cocoon silk, fastened to the mirror, and to the brass bobbin by a touch of shellac varnish, or marine glue. (See Fig. 15.) The bobbin is

Fig. 14.

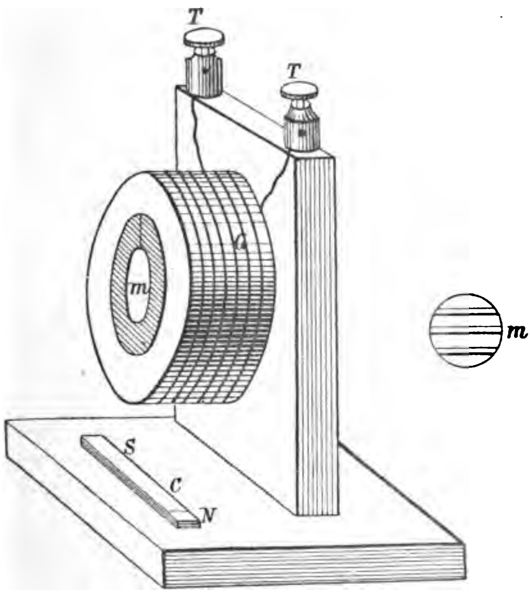


Lines or Rings of Force surrounding a Straight Wire conveying a Current.

attached to a board or vertical support. The back opening of the bobbin is closed with a cork, and the front by a watch-glass, to protect the mirror from currents of air. Such an arrangement is called a mirror-galvanometer. In order to adjust it for use the suspended magnets must be set parallel to the wire, and as in general the earth's magnetic force persuades them to take some other direction, it is necessary to have a small controlling magnet to cause the galvanometer needles to take the required position. If we throw on to the mirror a ray of light from a lime-light lantern, and reflect it from the mirror on to a screen, we get a

patch of light whose movement indicates the slightest change in position of the needle in the coil. Hence a very feeble current in the galvanometer coil declares its presence by causing the spot of light to move to one side or to the other.

Fig. 15.

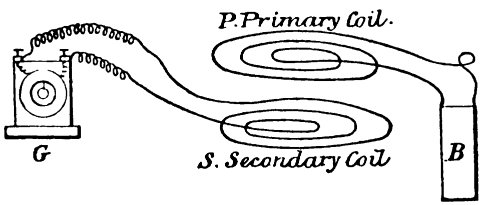


Simple Mirror Galvanometer.

To the terminals of the mirror galvanometer it is then possible to attach any circuit of wire and to detect and make visible the presence of an electric current in that circuit by a movement of the reflected patch of light on the screen. Let us proceed to follow Faraday in a series of experimental steps. I take a coil of about 100 feet of covered copper wire, No. 16 B.W.G., and attach the long

ends of the coil to the galvanometer. Placing this on the table, I lay over it a similar coil, separating the two by a board. The coil in connection with the galvanometer is called the secondary—the one on the top the primary coil. (See Fig. 16.) Having provided a few cells of a battery, we

Fig. 16.



Induction of Currents. G, Galvanometer; B, Battery.

commence operations by sending a current through the primary. The galvanometer needle gives a swing to one side, and then returns to zero. This indicates the passage of a brief wave of electricity through the secondary. As long, however, as the current in the primary makes no change, and as long as the position of the primary and secondary remain unaltered, no further indication of current in the secondary appears. Lift up the primary with the current still running through it, and move it away. The galvanometer declares the presence of a brief current in the secondary in the opposite direction. Move the primary again near, and we find another wave of current in the secondary. Now break the circuit and stop the primary current. The galvanometer indicates a response, by showing a transitory current in an opposite sense to that which occurred at making contact. A short examination of the direction of these currents enables us to sum up all the facts as follows:—

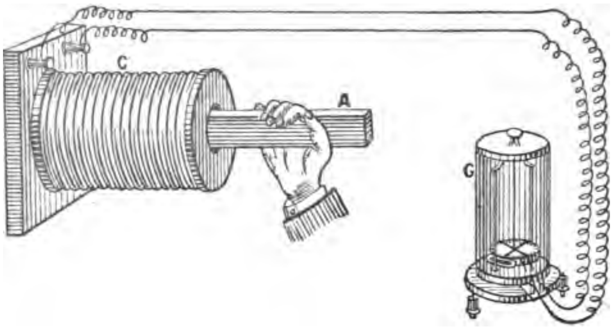
Starting a current in the primary, or moving primary

nearer whilst current is steady, produces a transitory current in the *opposite* direction in the secondary. Stopping the primary, or moving it away whilst kept steady, causes a transitory current in the *same* direction in the secondary.

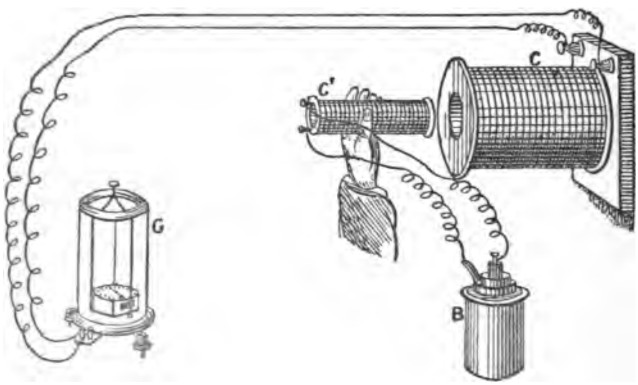
§ 13. It is evident, therefore, that the conditions under which a current in the primary coil can cause another current in a neighbouring secondary, depend upon some *change* either in the strength of the primary current or in the relative positions of the primary and secondary circuits. This fact, that a current of electricity in one wire can create a current in another wire, was called by Faraday the *induction of currents.* We may next note that this influence, whatever its nature, by which the primary *induces* a current in a secondary circuit is not affected by the interposition of any sheet of material which is non-magnetic and non-conducting. A wooden board, or a sheet of card-board, or a sheet of india-rubber, do not prevent the induction; but a thick sheet of copper greatly diminishes the effect, and a plate of iron prevents it altogether. Bearing in our recollection that a spiral or circular current affects all surrounding space, as would a magnet, we are prepared to follow Faraday one stage further. Lay aside the primary wire coil, still leaving the secondary attached to the galvanometer. Taking in hand a large steel bar magnet (see Fig. 17) we move one pole suddenly towards the coil. The galvanometer needle makes a violent deflection, indicating the presence of a strong transitory current in the secondary coil. As long as the magnet remains at rest it does not, however, affect the coil, and the galvanometer needle comes to rest. Now withdraw the magnet: a brief reverse current accompanies this withdrawal. It is evident, therefore, that the magnet does not by its mere presence cause an induced current, but that a *change* in the relative position of the magnet and secondary circuit is necessary to cause the brief wave of induced current in the secondary wire.

All the effects are greatly exalted in intensity if a short cylinder of soft iron is placed in the centre of the secondary coil.

Fig. 17.



Induction by a Magnet. C, Secondary Coil; A, Magnet; G, Galvanometer.

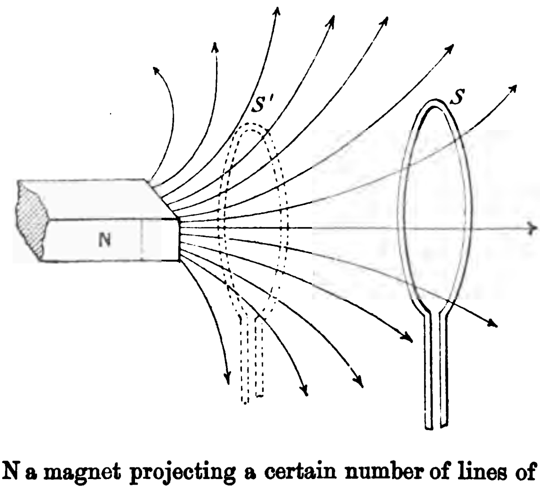


Induction by moving Primary Current. C, Secondary Coil; C', Primary Coil; B, Battery; G, Galvanometer.

§ 14. Without detailing the historical course of discovery in these phenomena of induced currents, we are able to group under one law all the effects so far described, and the

expression of this is called Faraday's law of Induction. It is as follows:—If any conducting circuit be placed in the magnetic field of a permanent magnet or of an electric current, then, if by either a change of relative position or a change of strength of primary current, a change is made in the number of lines of force passing through the secondary, an electromotive force is set up in the secondary proportional to the *rate* at which the number of included lines of force is varying. Consider first the simple case of induction by a magnet. Let S, Fig. 18, be a secondary circuit,

Fig. 18.

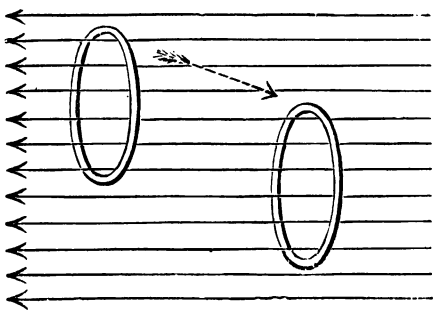


and N a magnet projecting a certain number of lines of force through the circuit. If S is moved nearer to the magnet, say to S′, a much greater number of lines of force of the magnet pass through the circuit when it is near than when it is far removed from the magnet, owing to the divergence of the lines as we get away from the pole.

§ 15. The law of induction shows us that since the rate of increase or of diminution of the number of lines of force

passing through a circuit is the measure of the induced electromotive force,* it follows that if a coil or circuit be moved in a magnetic field so that the number of lines of magnetic force passing through the coil is not altered, no electromotive force will be generated in it. If a circular coil move in a uniform magnetic field parallel to itself, no change takes place in the number of lines of force passing through it, and hence no induction occurs. (See Fig. 19.)

Fig. 19.



Circuit moved without Induction in a Uniform Field.

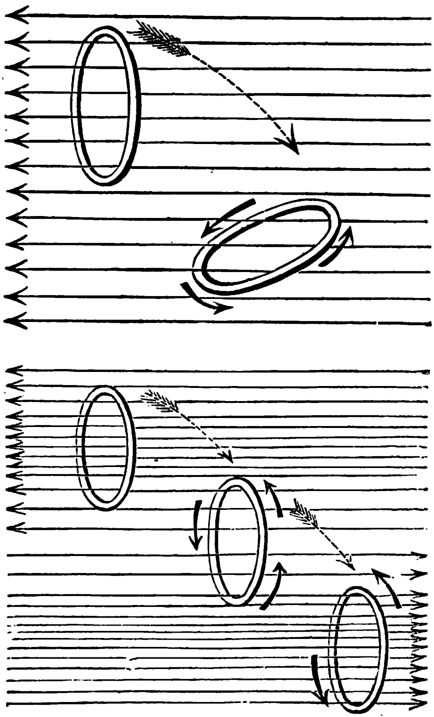
Again, if a coil be so moved in a field of any kind that its plane slides along lines of force, then, since this movement neither adds to nor subtracts from the number of lines of force passing through the circuit, there is no generation of induced current.

We see now, having regard to what has come under our notice in the first Lecture, the reason why a core of soft iron so greatly increases the induction current. It acts like a

* Electromotive force is defined to be that which sets electricity in motion, or makes a current of electricity. Just as water can only flow because of some pressure, so electricity can only flow urged by some electromotive force.

lens and concentrates or focuses more lines of force from the magnet or the primary coil through the aperture of the

Fig. 19A.



Circuits moved in Uniform and Non-uniform Magnetic Fields and producing Induction Currents by change in the Number of Lines of Force included.

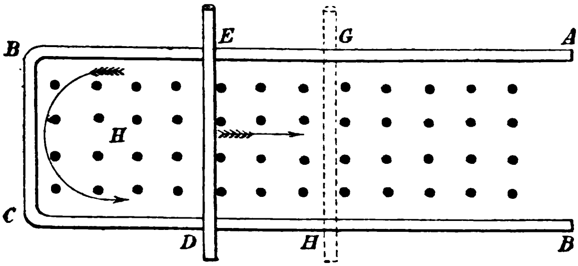
secondary, and therefore any movement makes a greater rate of change, and hence a greater induced electromotive force.

§ 16. A very little reflection will now convince you that the mere motion of a coil, especially if containing an iron core, without any magnets or primary current, should enable us to obtain an induced current in the secondary. Call to your remembrance that the earth itself is a great magnet, and that its lines of force pass through our atmosphere and spread out to a great distance into space. Brick walls do not stop lines of magnetic force, and this room is full of them. In our latitudes these terrestrial lines of force slope downwards at an angle of 67° 25′ to the horizontal, and lie in a direction 17° 54′ west of the true north and south line. I take this long coil of wire wound on a wooden bobbin and place in it an iron core. Connecting the ends of this bobbin with the galvanometer, I hold the bobbin so that its core points downward along the line of the earth's magnetic force, and then suddenly turn it round end for end so as to reverse its direction. The galvanometer needle makes a slight swing, indicating an electric current induced in the coil by the earth's magnetic lines of force. The turning of the coil effects an alteration in the number of lines of force passing through it, and this variation creates a transient current in the coil.

§ 17. We shall now examine a case of electro-magnetic induction of a simple character. Let us suppose a copper rod to be bent twice at right angles (see Fig. 20), and placed in a uniform magnetic field, so that the lines of force are at right angles to the plane of the bent wire. The section of these lines of force is indicated by the dots. Let a bar of copper be placed across these rails and held against them. Then imagine this cross-piece to slip along parallel to itself but still keeping contact with the rails. Think what will happen. When the cross-piece is at E D the area E B C D is traversed by a certain number of lines of force, and the total number of these lines poking through, divided by the area of E B C D, or the number per unit of area, is a measure

of the strength of the magnetic field in that space. When E D slides along, say to G H, the area is increased and the rate of increase of the area E B C D is a measure of the rate of increase of the number of lines of force passing through that area. The rate of increase of the enclosed area is

Fig. 20.



Induction by a Sliding Bar across Lines of Force.

measured by the product of the length of E D and its velocity, and hence the rate of increase of the number of lines of force passing through this area is the product of the strength of the field, the length of E D, and the velocity of E D parallel to itself. By Faraday's law, this rate of increase measures the force setting electricity in motion in the circuit E B C D, and if this circuit is a conducting circuit, as long as E D moves so long will the induced electromotive force urge round a current of electricity in the circuit E B C D. If the direction of the lines of force is perpendicular to the plane of the paper and *away* from the reader, then motion of E D to the right generates an induced current flowing round E B C D in the opposite direction to the watch-hand motion.

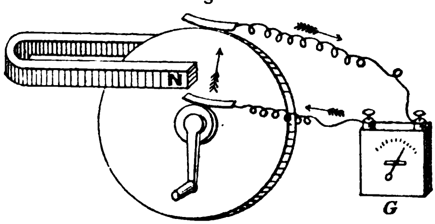
§ 18. We are now in a position to make a definition of what we mean by a *unit of electromotive force.* Suppose the magnetic field H to be of unit strength as defined in

Lecture I. Let E D be one centimetre long, and move with a speed of one centimetre per second. Then the electromotive force set up in E D will be one electro-magnetic unit of electromotive force. In practice this would be too small to use conveniently. Just as in coinage, a penny would be too small a unit for large transactions, and we call 240 pence one sovereign, so in electrical work 100 million times the electro-magnetic unit is called *one volt.* The electromotive force of one cell of a secondary battery is about two volts.

§ 19. Another typical case of induction by motion of a conductor in a magnetic field is interesting, because it was one of Faraday's earliest discoveries.

Let a copper disc be slung on a shaft and so balanced as to turn freely. A horse-shoe magnet is so placed that its inter-polar lines of force traverse the disc from side to side. A copper "brush" is placed so as to touch the shaft, and one to touch the edge of the wheel. (See Fig. 21.) A winch

Fig. 21.



Faraday's Disc Induction Machine. (The Disc revolves clockwise.)

or handle serves to rotate the wheel in the magnetic field. Now let the wheel be rotated clockwise, and if the north pole of the magnet is nearest the reader, the result will be to produce a radial current flowing out at the brush on the edge and back, through the brush on the shaft.

The explanation of this steady current is that each radial

portion of the disc is cutting across the lines of force of the magnet, and thereby becoming the seat of an electromotive force. We see from the experiment with the "sliding-piece" that when any conductor moves so as to cut lines of magnetic force at right angles, such "cutting" will cause an electromotive force to be set up in the revolving disc. We may consider the wheel to be divided up into spokes by radial slits, then each of these in turn passes across the field and becomes the seat of the induction.

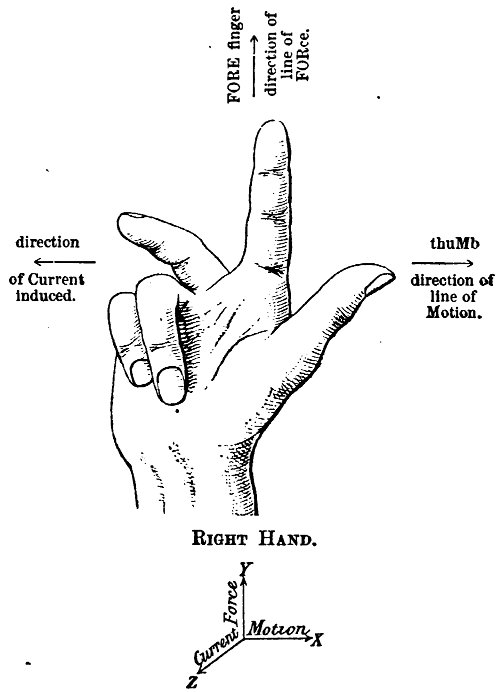
Faraday was enabled by the use of this machine to obtain a perfectly continuous current by rotation of a copper disc in a magnetic field, and, in fact, he made the first continuous current dynamo. Of late years the same principle has again been employed, and both Prof. G. Forbes and Mr. Ferranti have constructed disc machines of this type. In the case of Prof. Forbes' machine the disc is of iron, and moves in the strong field between two electro-magnet poles which completely cover the disc, and contact is made at the edge of the field by means of plumbago or metallic pressure pieces.

§ 20. Writers on electricity have given various rules for recollecting the direction of the current induced in a conductor when moved so as to cut lines of magnetic force and alter the amount of magnetic induction passing through the circuit. These rules depend generally on some association with the position and motion in swimming, or upon the direction of the cardinal points and the motion of the sun, earth, &c. Apart from the difficulty of recollecting the rules themselves, it requires an effort of imagination to apply them to the case of an armature, bar or wire, disc or loop, and as a means of economising time and brain labour the following rule has been found very useful.

If any circuit is being moved in a magnetic field, and it is required to know the direction in which electricity is being urged in any portion of the circuit which is cutting lines of force, proceed as follows:—Hold the first and middle

fingers and thumb of the right hand in a position as nearly as possible at right angles to each other, so as to represent three co-ordinate axes in space. Make the fol-

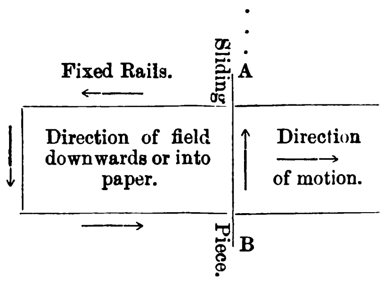
Fig. 22.



Three axes at right angles, indicating respectively direction of line of Magnetic Force, Y, line of Motion of Conductor, X, and direction of current induced, Z.

lowing associations:—Let the direction of the forefinger represent the direction of the lines of Force (FORe and FORce). Let the direction of the thumb represent the

direction at right angles to the direction of the field in which the element of the circuit is moving (thuMb and Motion), then the direction of the *middle finger* represents the direction of the induced current (Induced and mIddle). When once these links have been made, the directions of these three vectors will always remain related in the mind, and all that has to be done is to hold the right hand, with the fingers and thumb fixed in the position shown in the figure, and twist the hand about until the forefinger coincides with the direction of the field (which can always be ascertained by a pocket compass), and the thumb points in the direction of motion of the piece of the conductor considered (it will, of course, be in a tangential direction when considering a wire in a revolving armature), then, without any thought at all or references, either astronomical or natatory, the middle finger gives the direction of the actual or potential flow. A few simple cases considered, such as Faraday's copper disc between the poles of a horse-shoe magnet, or the usual illustration of a pair of rails and sliding piece, will serve to fix the rule.



Take the case of a sliding piece slipping parallel to itself on a pair of conducting rails. Let the direction of the field be perpendicular to the plane of the paper, and let the lines of force run *from* the reader. Then applying the rule, it is instantaneously seen that the direction of the current is in

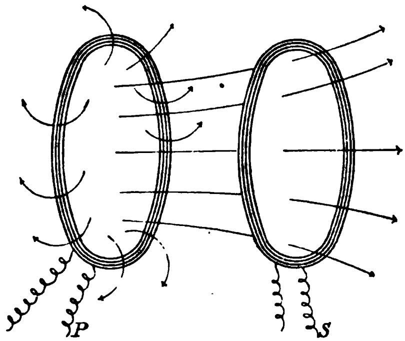
the direction of the arrow marked along parallel to the sliding piece, and that the current circulates round counter-clockwise in the closed part of the circuit, when the sliding piece A B moves to the right. The rule is easily applied to all parts of the armature of dynamo machines. Let it be observed that in finding the direction of the current induced we use the right hand, but if we use the *left* hand instead, it provides a rule for determining the direction of motion of a conductor under the influence of a field when traversed by a current. The same associations are made for the three directions, but as by Lenz's law motion is opposite for the same current or current opposite for the same motion, it is seen that the passage of a current creates a motion in the opposite direction to that motion which would have induced that current, because the left hand is the perverted image of the right hand. Hence we associate also *right* hand for *dynamos*, *left* hand for *motors*, directions of force, current, motion always in both cases indicated by the direction in which the forefinger, middle finger, and thumb respectively point.

§ 21. Returning now to the first case of a circular primary and secondary circuit, we picture to ourselves the primary current as sending out from its positive face a stream of lines of force. Some writers call this the flux of force of the current. If a secondary circuit is brought near to a primary coil, a portion of the lines of force proceeding from the primary pass through the secondary. (See Fig. 23.) Just as the earth receives some, but not all the rays of light which come out from the sun, so the primary current projects lines of force, some, or perhaps all of which may pass through the secondary. If a unit electric current is passing through a primary coil the number of lines of force which it projects through the secondary coil is called the coefficient of mutual induction of the coils.

§ 22. We have not before defined what we mean by unit

current. Let a thin wire be bent into a circle of one centimetre radius. Each portion of this wire is equidistant from the centre. Suppose a unit magnetic pole held at the centre of this circle, and let the magnet be so long that the other pole

Fig. 23.



Lines of Force from a Primary Coil P traversing a Secondary S.

is removed out of the way. Let such a current be passed through this circular conductor that each unit length or centimetre of the current acts with unit force (one dyne) upon the unit pole, or the whole circular current acts with force of 6·28 dynes upon the pole. This current is called the *unit electro-magnetic current*, and one-tenth part of this unit is called *one ampère.* Accordingly the absolute unit of current is ten ampères.

§ 23. Not only does a current at starting and stopping or changing strength act on neighbouring conductors, and so generate induced currents in them, but it acts upon itself by a process which is called *self-induction.*

Consider the action of a current just starting or increasing in a wire upon a neighbouring parallel wire. The inductive action creates an oppositely directed momentary current in its neighbour; *also* it creates an oppositely directed momentary

current in itself. This self-opposing current has to die away before the actual electromotive force can bring the current in the conductor up to its full strength, and the result is that the current in a wire cannot, and does not rise up suddenly to its full strength, but rises gradually as the initial self-induced electromotive force dies away. Again, on breaking the circuit in which a current is running, this self-induction creates a momentary induced current in the *same* direction as the current being interrupted. This electromotive force of self-induction on breaking circuit may have a higher value than the steady force maintaining the current. It is as if the current starting in a wire built up a little obstacle to its own motion at first, and on stopping the current received a little push so that it tended to run on. Or we may put the matter in another way. The current moving in a wire behaves just like a heavy flywheel being set in motion. You cannot start a heavy wheel full speed all at once because of its *inertia*, and you cannot stop one running suddenly. The similar behaviour of a current has won for this property the name of *electric inertia*, which term is sometimes used instead of self-induction. The student, however, must not fall into the error of supposing that the current itself possesses momentum. The general opinion on the matter is that the property of electric inertia is due to the fact that the current has to set up some kind of motion in and around the conductor, and that this motion constitutes the magnetic field. Hence a magnetic field cannot be brought into being, so to speak, immediately. The circular lines of magnetic force round a straight current do not spring into existence suddenly when the current begins, but expand out gradually, like the widening ripples when a stone is dropped on to still water, and when the current ceases, these lines collapse gradually again on to the wire and do not disappear instantaneously in the place where they are. The curious thing is that the collapse back of the lines of magnetic force on to the wire

may, for a moment, give rise to an electrical "push," or electromotive force far greater than the steady force which maintained the current, and this sudden drive forward of electricity in the wire at the instant when the circuit is broken, causes the bright spark seen whenever a strong current is interrupted. You know that when the "switch" of the magnet circuit of a dynamo is broken we get a much brighter and stronger spark than when simply breaking the same strength of current not running in a circuit containing a magnet. You will not have much difficulty in inferring the reason. If a current is running in a wire round a magnet owing to the permeability of the iron, a far larger number of lines of force traverse its own circuit, or are linked with it, than if the iron core was removed, and hence, at the stoppage of the current, a correspondingly great electric impulse of self-induction operates in the wire and creates a spark.

If any one has any difficulty in understanding how this "extra current" of self-induction at breaking can have a greater electromotive force than that which maintained the steady current, help may be derived by comparing the phenomenon with that appliance called an hydraulic ram, in which the impetus of running water is made to lift a portion of its mass to a level higher than that from which it fell. The action of self-induction at breaking a circuit is very much analogous to the blow which a high-pressure service water-tap experiences when the full flow of the water is suddenly arrested by turning off the tap. The water momentum will often burst the pipe. Similarly the action of self-induction often breaks through the insulation of field magnets when the current is suddenly arrested in them. . . .

We may regard the action of the self-induction as a spurious resistance, introduced into the conductor at the moment when a current begins to flow in it, and which resistance is gradually removed. This self-induction is

much greater in the case of a coil of wire than if the same wire is laid out straight. In magnitude it is proportional to the square of the number of turns of the coil. It is also greatly increased by introducing an iron core into the coil, and will be increased proportionately to the permeability of the iron.

The action of this self-induction is to hinder the sudden rise and fall of current strength in a wire. Hence in circuits with large self-induction it is not possible to make very *sudden* changes in the strength of a current flowing through it. This it is which hinders telephonic transmission of speech through long coils of wire. A striking experiment on self-induction is to introduce a coil of wire into the circuit of an alternate current dynamo machine, feeding incandescent lamps, and then when the current has become steady, to suddenly insert a thick iron bar into this coil. The greatly increased self-induction manifests itself by the diminution in the light of the lamps. Self-induction causes an apparent increase in the resistance of armatures of dynamo machines whilst running. When we consider that such armatures consist of rings or drums of iron wound over with loops or coils of wire in which currents are being rapidly reversed, it is easy to see that this property of self-induction must manifest itself by rendering the change of the currents more sluggish than it would otherwise be. We define the coefficient of self-induction of any conductor, straight or coiled, as the amount of electro-magnetic energy associated with it when one electro-magnetic unit of current is flowing through it. The quotient of the coefficient of self-induction of a coil by its resistance, is called the *time constant* of that coil. This is the time in seconds or fraction of a second, in which the current will rise to a definite fraction, about $\frac{43}{68}$ of its full or final value.*

* The fraction $\frac{43}{68}$ is equal to $\frac{e-1}{e}$ where $e = 2{\cdot}71828$ the base of nap logs.

It is useful to bear in mind that the kinetic energy of a current, that is the energy of its motion, is measured by the product of the coefficient of self-induction, and half the square of the current strength. We find a parallel to this in the case of the energy of a moving body, in which case the kinetic energy is the product of the mass, and half the square of the velocity. The self-induction of a wire depends upon the magnetic permeability of the material of which it is made. Hence an iron wire has a greater self-induction than a copper wire. It also depends upon the form of its section. A flat ribbon has less self-induction than the same mass of metal in the form of a round wire. Accordingly conductors, such as lightning-conductors, intended to carry sudden discharges, should have the form of a flat ribbon of copper.

Professor Hughes has shown* that a stranded iron wire cable has less self-induction than one of the same mass of metal formed into a solid wire. The explanation of this is that the circular field of magnetic force round the axis, which exists inside the wire as well as outside, is not so strong in the interior of the stranded iron cable as in the interior of the solid iron rod. The stranding reduces the magnetic permeability along lines which are circles described round the axis, and hence reduces the self-induction.

* See Presidential Address to the Society of Telegraphic Engineers and Electricians, by Professor Hughes, F.R.S., February, 1886.

LECTURE III.

§ 24. Reference has already been made to the nature of the magnetic field of a helix of wire, or a solenoid. We may construct such a solenoid by taking a pasteboard tube with wooden flanges or cheeks glued to the ends, and winding on it cotton-covered wire evenly and closely from end to end. Let a bobbin of this kind be made by winding on a tube, say one inch in diameter and eighteen inches long, a closely wound layer of No. 16 B.W.G. cotton-covered wire. If we pass a current of five or six ampères through this coil and test the interior by means of a small magnetic needle, it will be found that the lines of force inside the core, and at a distance from the ends are straight, and parallel to the axis. By introducing a piece of card into the tube covered with iron filings, and then passing a strong current, we shall find the filings delineate a series of lines parallel to the axis of the tube. If we measure the length occupied by the wire windings in centimetres, and also the number of turns which the wire makes, and divide the number of turns by the length of the coil in centimetres, we get the number of turns per centimetre of length. If we measure the current going through the wire in ampères and multiply it by the turns per unit of length we get the ampère turns per unit of length. It is not difficult to prove that $\frac{44}{35}$ths of the ampère turns per unit of length gives a number which expresses the strength of the magnetic field in what is called absolute measure. This number is also called the magnetising power of the solenoid. In some dynamo machines, such as the Edison, the field magnets are cylindrical cores of soft iron wound over

with cylindrical layers of wire. To obtain the magnetising power of such coils, count the total number of turns made by the wire, multiply it by the strength of the current running through the coil, divide the product or ampère turns by the length of the coil in centimetres, and multiply by $\frac{44}{35}$. The result is the strength of the magnetising field at the centre of the coil. This rule cannot be applied to short coils, or coils in which the length is not at least a dozen times as great as the diameter. Nor will it give correctly the field strength near the ends of the coil, but only at the centre.

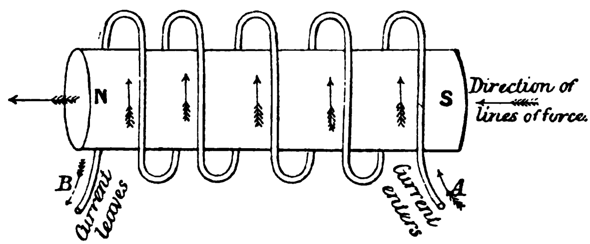
§ 25. Although before 1820, one philosopher, Ritter, had considered he had obtained magnetic effects from an electric current, it was not until that year that the matter was definitely settled by the great discovery of Oersted of the action of an electric current in producing round its conductor circular lines of magnetic force. On September 25th, 1820, Arago announced to the Academy of Sciences that he had demonstrated that a wire of copper traversed by an electric current would attract iron filings, and that the same attraction took place whether the wire was brass, silver, or platinum. It was found that if a wire conveying a current was placed at right angles to a needle of iron or of steel the needle was magnetised permanently if of steel, but merely temporarily if of iron. Discovery was soon made of the fact that very powerful magnetic effects could be produced by surrounding a bar of iron with a coil of insulated wire conveying a strong current of electricity. These facts laid the foundation for the science of electro-magnetism. Ampère's important discoveries then followed, in which he showed that conductors conveying currents act upon one another like magnets, and he established the fact that a very small circular current acted upon all surrounding space precisely as would a thin circular disc of steel of the same radius magnetised normally or perpendicularly to its face. It was finally found that the short discharges of electricity, like

those from an electric machine or Leyden jar, or a flash of lightning, magnetise iron and steel when they pass across it.

If a wire of very soft iron is magnetised, and then handled very gently, so as not to shake out of it the slightly held magnetism, such a wire is instantly de-magnetised by sending along it a sudden discharge of electricity.

§ 26. If a bar of soft iron is placed in a helix or spiral of wire, and a current sent through the wire in such a direction that when looked at end on, the current appears to revolve round right-handedly, or like the hands of a watch, then that end nearest the eye is a south or blue pole. The direction of the acquired magnetism of the iron is in the same direction as the field of the empty solenoid or helix. (See Fig. 24.) Any such iron bar or plate, no matter of what form, surrounded with coils of insulated wire through which a current can be passed, is called an electro-magnet.

Fig. 24.

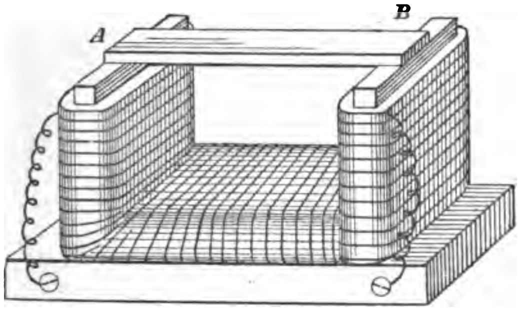


Poles of an Electro-magnet.

In electrical workshops a powerful electro-magnet is often required to magnetise steel bars or needles. One of the best forms of electro-magnet for such a purpose is made thus. A strip of very soft Swedish iron is taken, about two feet long, three inches wide, and one inch thick. This is bent twice at right angles about six inches from either end, so as to make a horse-shoe shape. The ends may be planed

flat. This horse-shoe is then wound over from end to end with half-a-dozen layers of No. 12 B.W.G. double cotton-covered wire, and the whole mounted on a convenient wooden stand. (See Fig. 25.) If, through such a magnet,

Fig. 25.



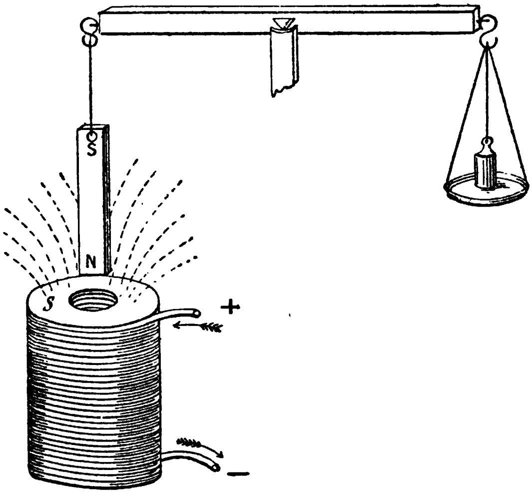
Workshop Electro-magnet.

20 ampères of current is passed from a few secondary cells, very powerful magnetism is excited in the iron core. A steel bar to be magnetised can then be placed across the poles and hammered with a wooden mallet whilst the current is passing. A few minutes suffice to magnetise the steel to saturation. If it is desired to magnetise small needles, such as compass-needles, then soft iron plates may be used as pole pieces to enable a small needle, such as a compass-needle, to bridge across the interval and so be magnetised.

§ 27. A coil or helix of wire traversed by a current, exercises a strong attraction upon a bar of soft iron held along its axis. To exhibit this effect, the following experiment suffices:—Balance on a scale beam a rod of soft iron, and bring under the bar a coil of wire. (See Fig. 26.) On passing a current the bar is sucked into the coil strongly The reason is not difficult to find. The inductive action of the coil develops a magnetic pole at the lower end of the

iron bar of an opposite kind to that of the coil uppermost, or nearest to it, and a pole of a similar kind in the end farthest from it. These poles find themselves in fields of very unequal strength; the field of the coil is strongest at the point where the opposite pole is, and weakest where the similar pole is, hence the iron as a whole is attracted.

Fig. 26.



Attraction of Magnetic Pole by Helical Current.

It should be borne in mind that a piece of iron as a whole has no tendency to move along lines of force of a uniform field, but if one end is in a place of stronger field than the other, the iron will tend to move until equilibrium is established between the forces acting on both ends of the bar. If the iron rod is free to move it will be sucked into the solenoid until it is symmetrically placed with respect to it, that is, until the forces on each end of the bar are in equi-

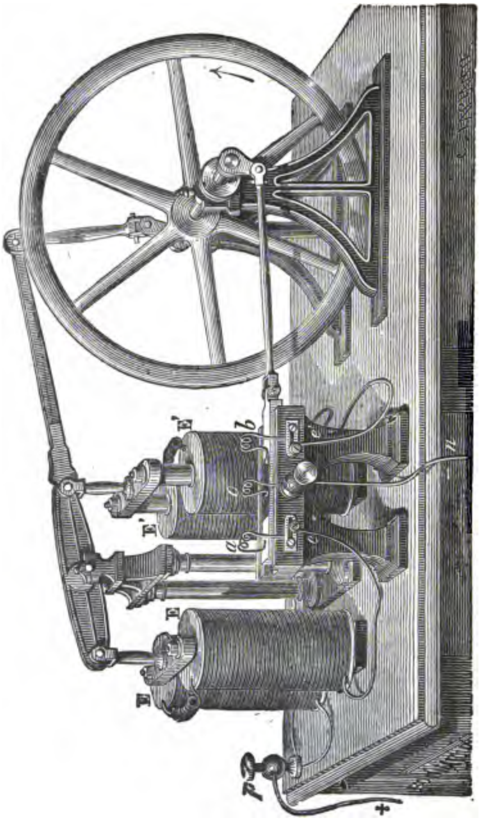
librium. This behaviour of a soft rod of iron in a helical current has been made the foundation of a magneto-electric motor, called after its inventor, Bourboize's motor, in which motion is communicated to a flywheel by pistons of soft iron which are alternately sucked into cylindrical coils of wire, current being distributed to each in turn by a sort of slide-valve arrangement. (See Fig. 27.) The alternate pulls of solenoids operating on plungers of soft iron attached to opposite ends of the beam is made to produce oscillatory motion, which is converted to circular motion by means of a crank.

It is hardly necessary to point out that if instead of suspending a bar of soft iron from the scale beam, we had employed a magnet, then we should have had attraction or repulsion, according as the end of the magnet presented to the solenoid is an opposite or a similar pole.

§ 28. We can avail ourselves of the magnetic field due to the earth itself, to effect the magnetisation of soft iron. Whatever may be the cause of the permanent magnetism of the earth, the earth as a whole affects space exactly as if it were surrounded by electric currents, following in a certain irregular manner the direction of lines of latitude, but more or less inclined to the direction of these lines. Hence it follows that the space round the earth is traversed by lines of magnetic force. If then, at any place, a bar of iron is held parallel to the direction of the terrestrial magnetic field, it will acquire magnetism by induction. This magnetism is, however, very feeble. To exhibit to you this effect, I take a bar of exceedingly well annealed soft iron, about one inch in diameter, and eighteen inches long. It is necessary to prove in the first place that it is already destitute of permanent magnetism. I present each end of it successively to a delicately suspended magnetic needle; in each case we find the end of the iron bar *attracts* the compass-needle feebly. This proves that the iron is magnetic, but not magnetised.

The compass-needle pole develops by induction an opposite pole in the end of the soft iron presented to it, and attraction takes place. Now, holding the iron bar in a direction in-

Fig. 27.



Bourboize's Electric Motor.

clined at an angle of 70° to the horizon, and pointing downwards in the direction of the magnetic meridian, I strike the iron with a wooden mallet. Keeping it in the same

direction we employ the compass-needle to test its ends. See what happens; the north end of the compass-needle is attracted by the upper end of the bar, but is repelled by the lower end. This shows that the iron bar is now magnetised. Turning the iron bar upside down, the experiment is repeated, and it is found that the poles are reversed, and that the lower end of the iron bar, which was a moment ago the upper end, is now a north pole, and attracts the south end of the compass-needle, and the upper end now attracts the north end. A reversal of position, combined with a blow, has sufficed to reverse the magnetisation a moment ago imparted to the bar. The magnetisation by terrestrial induction is found in every bar or beam of iron which has been long in a vertical position. Test with a pocket compass a dozen iron railings selected at random, and you will find each vertical bar attracts the south pointing end of your compass at its lower end, the opposite at its upper extremity in our latitude.

§ 29. No one who has experimented with an electro-magnet can have failed to notice that the effect of magnetism lingers in an iron core long after the current has been stopped. This effect of residual magnetism is more apparent in what are called closed magnetic circuits. Across the poles of the horse-shoe magnet (figured in Fig. 25) place a broad plate of soft iron and excite the magnet strongly; stop the current and you will find that the plate is still held with some force by residual magnetism. And this will be greater if the ends of the poles and the plate are well planed so as to fit together. Now detach the plate by a good pull, and replace it. It will be found that no such effort will be needed to remove it again. Some magnetism therefore lingered in the magnet, which was dissipated by the act of once opening the iron circuit.

§ 30. At this stage of our studies it will be convenient to assist the memory and the mind by a further reference to

the explanation which was given in our first lecture. Take a magnetic needle, break it in half, we get two complete magnets, each with a pair of opposite poles. Continuing the process we get the same result. We are forced to the conclusion that each little particle of a magnet is itself a magnet. Taking our glass tube of steel filings, we magnetise it, and test it by a compass-needle; you will find it behaves like a permanent magnet, that it has two poles, and that if hung up by its middle by a silk thread it will point to the magnetic north. Loosen the cork and shake the tube, so as to mix up the filings completely, and test the tube again. All traces of magnetism will have vanished from it. Why is this? The little particles of steel still retain their individual polarity, but their irregular arrangement renders the total action of all of them zero. Imagine that by some magic we rearrange all these countless little steel magnetic particles in the original positions, the whole tube would now exhibit its magnetic qualities again. Based on these facts the following theory of magnetism has been propounded. Particles of iron and steel are always magnetic. In an ordinary so-called un-magnetic iron or steel bar, the arrangement of these little molecular magnets is irregular, hence there is no external or apparent magnetism of the mass. Magnetisation consists in arranging them regularly, so that their magnetic axes all point in the same direction. Further, we have to make two suppositions. If in turning round a magnetic particle to make its axis take a certain direction we have to twist the molecule much, then it acquires a permanent *set*, and will not spring back to its old position when the force is removed. The resistance which a magnetic particle opposes to being so twisted, increases with the amount of twisting. In steel, we must suppose that in addition there is something of the nature of friction between the molecules which tends to preserve them in positions in which they happen to be. On these suppositions it is

possible to account for some of the phenomena of magnetisation. Let a magnetising force act upon a bar of iron. Suppose it small at first. It suffices to impart a uniform direction to a few of the molecules whose magnetic axes are already nearly directed along this line. It develops, therefore, a feeble magnetism in the iron. Let the magnetising force increase, it compels more and more of the molecules to submit to its directing power. At last a limit is reached, when all the molecules have their magnetic axes directed in the same direction. No greater magnetising force can do any more. This is the point of saturation. Suppose the magnetising force withdrawn. If the bar be of steel the molecular friction is great enough to prevent very much falling back of the molecules to their old irregular positions. This exhibits, therefore, permanent magnetism. If the bar is of soft iron the disappearance of this magnetising force is accompanied by a falling back to their old positions on the part of the molecules. Some of them, however, have been wrenched round so far that they have acquired a permanent *set*, their limit of perfect magnetic elasticity has been overpassed, and they remain in the direction imparted to them and constitute the cause of residual magnetism. Violent blows or knocks may, however, send them back to their old positions, hence the residual magnetism can be so removed. Heat, by causing a molecular agitation, removes magnetism, both permanent and residual.

These magnetic facts have their complete parallel in the phenomenon of *torsion* of wires. Take a brass wire, slightly twist it; when released it springs back completely. Twist it still more, release it, a slight permanent twist remains. This is residual magnetism. Take a lead wire, twist it, release it, it does not spring back, but retains its torsion. This is permanent magnetism. Many other facts combine to indicate that magnetisation of iron and steel is accompanied by some movement and re-arrangement of the particles.

Place your ear close to a large electro-magnet, and get a friend to start a current through the coils by completing contact at a distant spot. You will hear a slight *tick* or sound at the moment of magnetising the iron. If iron is magnetised and de-magnetised rapidly, these ticks run together into a sort of musical note, and the intensity of the note can be exalted by a sounding-board.

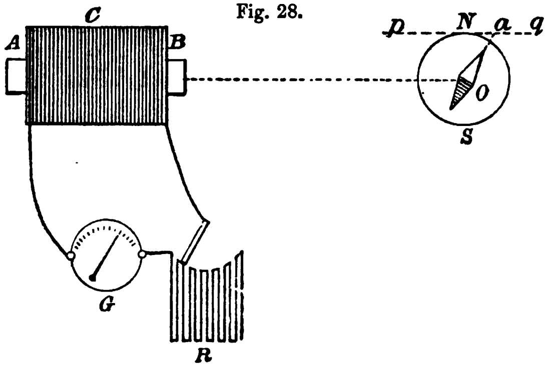
Also, the magnetisation of an iron bar is accompanied by a change in its dimensions. It is possible to prove by very refined experiments that a bar of iron is lengthened by magnetisation up to a certain limit of magnetising force; beyond this limit further increase of magnetising force shortens the bar. The subject engaged the attention of Mr. Joule, in 1842, and far more recently that of Mr. Shelford Bidwell, and it is to him that we are indebted for the fact that the initial expansion of iron under weak magnetising forces is succeeded by a subsequent contraction in length under strong magnetising forces. It has been shown that no alteration in volume is produced by magnetisation, so that a contraction in diameter must accompany an increase in length.

§ 31. The foregoing theory, generally called Weber's theory of magnetism, helps us to understand that which would otherwise be very perplexing, viz. the saturation of iron magnetically; in virtue of which it is not capable of holding more than a certain number of lines of force, or of attaining more than a certain intensity of magnetisation.

The following experiment shows how we may best study the question. Let A B (Fig. 28) be a bar of very soft Norway iron, surrounded with a helix of wire, through which we can pass a gradually increasing current, measured by the galvanometer, G, and varied by the introduction of resistance, R. In line with the axis of the bar, and at a considerable distance from it, let a compass-needle be placed, and let the whole apparatus be so disposed that when no current is

passing the compass-needle may be at rest in a direction at right angles to the line of the axes of the bar. That is, the bar must be directed magnetic east and west. Pass a small current through the coil measured by the ammeter, G. The

Fig. 28.



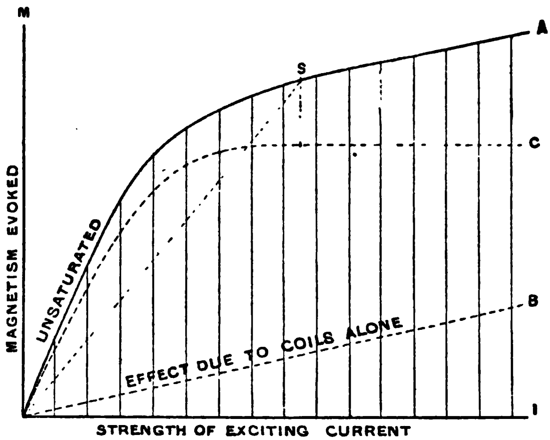
Measurement of Magnetisation of Iron.

result is to produce a deflection of the compass-needle. The needle is pulled round in a direction more or less inclined to the direction of the meridian. Let the compass-needle be placed upon a sheet of paper, and let a line, *p q*, be drawn, touching the compass-card at N and parallel to the line O B, joining the centre of the compass and the bar A B. Suppose the compass-needle pulled round into a position as figured. Produce the direction of the needle of the compass by drawing a line with a pencil until it cuts the line *p q* at *a*. Then the length of the piece of the line N *a* between the point to which the needle is directed when at rest, and the point to which it is directed when deflected, is a measure of the strength of the magnetic field at O, which is due to the electro-magnet A B.

Take a sheet of squared paper, and on the bottom edge set off from the left-hand bottom corner lengths representing

the measure of the strength of the current as given by the ammeter, G, and perpendicular to these points run up distances proportional to the length N a, or to what is called the tangent of the deflection of the compass-needle. Proceed to observe deflection for many different strengths of current passed through the coil, and plot out the results on a curve. We shall get a curve like the thick upper curve in Fig. 29. This curve represents the field at O, due to

Fig. 29.



Curve of Saturation of an Electro-magnet.

the combined effect of the coil C and the bar A B, which is magnetised. Remove the bar without disturbing the coil and repeat the experiment, and plot as before on the same paper a curve showing the field at O, due to gradually increasing current in C. We shall get a curve which is a straight line slanting regularly upwards from the origin. This shows us that the magnetic field of a solenoid is at every point proportional to the current flowing through

it. The joint effect of the bar and coils is the sum of the effects of each separately. Let us therefore deduct from each vertical ordinate of the thick curve the corresponding ordinate of the straight line, and we get a resultant curve such as C, which is the effect of the bar alone. We note that after slanting upwards, this curve has a knee or bend and then becomes horizontal. We have thus represented to us graphically the fact, that at first increasing strengths of magnetising current, increase the magnetic field at O due to the bar alone, but that after a certain strength of magnetising current is reached no further increase increases the strength of the field at O due to the bar alone. This inner curve, which represents not only the magnetic field at O, but also the intensity of magnetisation of the bar, is called the curve of magnetisation of the iron, and the point where the curve becomes flat, represents the point of saturation of the iron.*

§ 32. If a soft iron ring is taken and lapped over regularly with a length of covered wire, we have what is called a ring or annular electro-magnet. Such a magnet has no poles, and if the composition of the iron were perfectly uniform it would exhibit no external magnetic action. The ring, however, is powerfully magnetised when a current is passed through the wire. The total number of lines of magnetic force running round the iron circuit is called the total induction, and the number of lines of force per unit of cross sectional area of the ring is called simply the

* It is a point of great interest to determine, if possible, what is the exact relation between the magnetising current and the strength of the field at O due to the magnetism of the iron alone. If the strength of this field is H and the strength of the current is i, then $H = \frac{i}{a + b i}$ nearly. It is easy to see that if a and b are constants, when i is very small, H is nearly proportional to i, but when i becomes very great then H is equal to $\frac{1}{b}$ which is a constant.

magnetic induction in the ring. Imagine the ring cut through at one place and the ends a little separated, we get a nearly closed magnetic circuit. The air gap, however, which interrupts the iron circuit is less permeable than the iron, and hence with the same magnetising force the total induction is less than before. This is a case analogous to that which we have in every dynamo machine. There we have an electro-magnet called the field magnet, and between the poles of this is an iron core wound over with layers of wire. The iron core does not of course touch the pole pieces, because space must be left for the copper wire and for clearance, hence the iron circuit of the magnet has two air gaps in it. The resistance to the flow of lines of magnetic force round the iron circuit is mainly due to the resistance of this air gap, and hence to obtain a very intense field in the place where the copper wire is, this air gap should be made as small as possible and its magnetic resistance be decreased both by making it thin and by increasing the area of pole pieces within certain limits.

It is often necessary to be able to measure the magnetic field in an air gap, in between the poles of an electro-magnet. The best way to do this is to take a length of covered wire and make a loop at the middle, or to take a small flat coil of wire and twist together the leading wires. This coil or loop should be placed in the magnetic field to be measured, and the ends of the leading wires attached to a galvanometer having a very freely suspended needle. The loop is to be held so that its plane is perpendicular to the lines of force of the field. On snatching away suddenly the coil or loop all the lines of force which passed through it are cut through or removed from it, and the removal of these lines creates an induction current in the loop, which evidences itself by making a sudden swing of the galvanometer. If a reflecting galvanometer is used, and if the swing of the needle does not extend more than a few degrees of arc, the

strength of the field is proportional to the extent or amplitude of the swing. In order to obtain an absolute measure the same experiment must be performed by placing the coil or loop in a magnetic field of known strength. This can be done by holding it in the interior of a helix of wire, traversed by a known current, and of which the interior field can be calculated when we know the ampère-turns per unit of length. In order that accurate results may be obtained, the galvanometer needle should not only be very freely suspended, but be so heavy that the whole electrical discharge may take place before the needle has time to move; and the vibration of the needle should be as little as possible retarded by friction of the air.

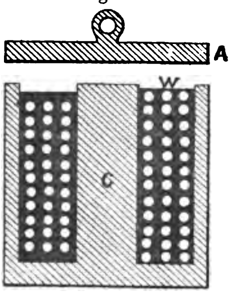
LECTURE IV.

§ 33. The form which an electro-magnet should have, depends upon the nature of the operations it is used to perform, or the purpose to which it is to be put. A design of electro-magnet, which is very suitable for some purposes, is very unsuited for others. Supposing it is desired to make an electro-magnet which shall be capable of rapid changes of strength, or possess small residual magnetism, it should be made of very soft Norway or Swedish iron, and have the form of a short stout bar, rather than a long thin one. The reason for this is that the ends or poles of a magnet exert a de-polarising action upon the mass of the interior of the magnet. If the iron bar has the form of a long thin bar, or a wire whose length is, say, 300 times as great as its diameter, then the poles or ends are very far removed from the middle, and the de-polarising action is feeble, and such a long thin magnet, even though made of very soft iron, will retain a good deal of residual magnetism after the magnetising force is removed. On the other hand, a short thick bar quickly de-magnetises itself even without the assistance of shakes or twists. For the same reason a ring magnet, with no free poles, retains residual magnetism to a very great extent. When, as in many telegraphic instruments, a piece of soft iron called an armature is to be attracted to the poles of a horse-shoe shaped electro-magnet, this armature should be prevented from quite touching the polar faces of the magnet, either by the interposition of paper or of a brass stud. If the soft iron mass does quite touch the poles, then it completes the magnetic circuit, and

abolishes the free poles, and the magnet is deprived to a very great extent of its self de-magnetising power. This is the explanation of the well-known fact that after magnetising an electro-magnet and then stopping the current, it still requires a good pull to detach the "keeper," but when once the keeper has been detached, the iron exhibits comparatively small magnetic qualities. If the use to which the electro-magnet is to be applied is that of attracting a soft iron keeper or armature, then its form will depend upon whether that attraction or pull has to be exerted over a large or small distance. In the case of ordinary horse-shoe electro-magnets with flat poles, the strength of the magnetic field diminishes very rapidly as we recede from them, and accordingly such magnets, though attracting with considerable power when the armature is very near the poles, exercise but little force on the armature when it is a short way removed from the poles. It was this fact which rendered the early efforts to construct electro-magnetic engines so fruitless. If it is desired to construct a magnet which shall exercise a strong pull upon a keeper at a very short distance, then the magnet should be of horse-shoe shape and have broad flat ends kept far apart, and the keeper to be attracted should also have large surfaces opposed to the polar ends, and its cross section should not be less than the least cross section of the iron of the electro-magnet. In the case where a bar electro-magnet is used, increased effect is obtained by surrounding the bar with a tube of soft iron attached at one end to the base plate which carries the bar, and having the other edge level or flush with the polar end. (See Fig. 30.) The outer iron case serves to conduct up lines of force from the opposite pole of the magnet, and to strengthen the field just above the polar surface of the magnet. If the electro-magnet is employed to produce a pull over a great distance, means must be adopted to prevent such a rapid rate of diminution of the field in receding from

its poles. An ingenious device for doing this is adopted in the Thomson-Houston dynamo, and is also applied in the arc lamps of the same inventors. The pole of the electro-magnet is prolonged into a sort of nose (see A, Fig. 31), and the armature to be attracted is pierced with an aperture through which this nose protrudes. The effect of the contrivance is to render the pull of the magnet on its armature more uniform and operative over a greater distance. At one time Mr. Joule occupied himself a good deal with the question of the best method of producing electro-magnets which could support great weights, or which could exercise immense attractive power over armatures in contact with

Fig. 30.



Tubular Electro-magnet.

Fig. 31.

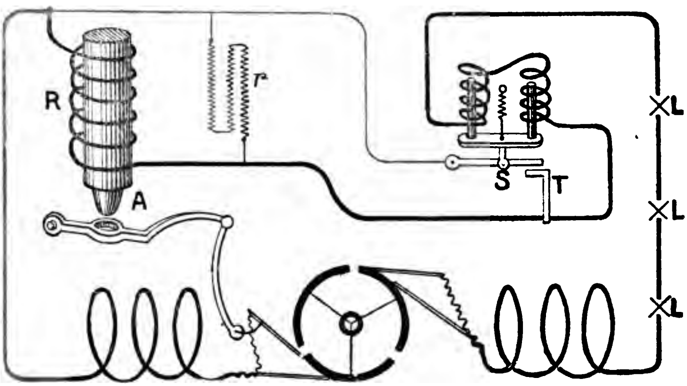
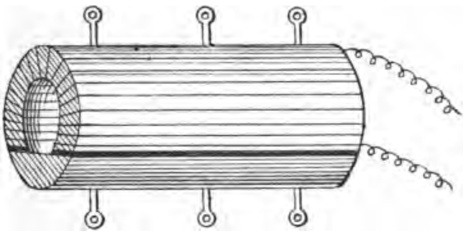


Diagram of the Connections of Thomson-Houston Dynamo.

their poles. After many experiments he discovered that the most effective form was obtained by taking a thick

cylinder of soft iron, boring a hole lengthwise through it, planing over one side of the cylinder, so as to expose the longitudinal hole, and providing the horse-shoe sectioned bar with a long segment-shaped piece of soft iron, as a keeper. (See Fig. 32.) The iron cylinder was then wound

Fig. 32.



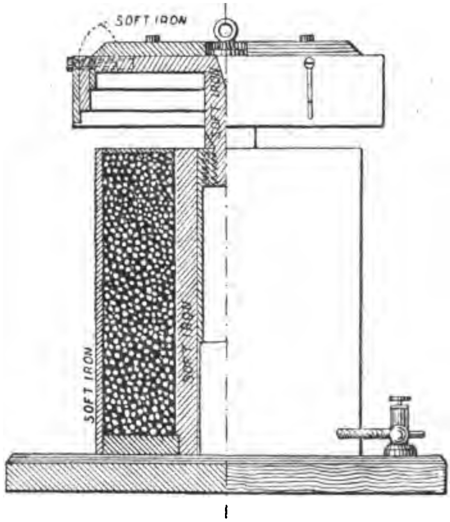
Joule's Electro-magnet.

over lengthwise by strands of insulated wire, and the magnet and keeper provided with means for supporting and attaching to them weights respectively. Mr. Joule in this way constructed a magnet weighing only 15 lbs., but which could support a weight of 2090 lbs.

A magnet, devised by Mr. Currie as a long-pull electro-magnet, for working railway signals at a distance, is constructed as shown in Fig. 33. The magnet is a tubular magnet, or solenoid wound on a brass tube with an outer iron sheath. The armature is a mushroom-shaped piece of soft iron. The stalk is conical, and projects into the solenoid. The action of the magnet is supposed to be something as follows :—The first operation is the attraction of the stalk into the core, then as it enters the core, the force on it gets less, but the mushroom head now is approximated to the polar surfaces of the outer iron sheath, and it in turn attracted. The joint effect being to give a considerable pull over a large range. The general principles which underlie the construction of electro-magnets

for different purposes are as follows :—The magnetic field, and hence the magnetising power of a long solenoid or helix of wire, is proportional to the number of ampère-turns per unit length, or to the product of the strength of the current, and the number of turns of the wire per unit of length of the coil or core.

Fig. 33.



Currie's Long-pull Electro-magnet.

Multiplying the total number of ampère-turns on the magnet by $\frac{4\pi}{10}$ gives what is called the magneto-motive force of the helix. If the number of lines of force per unit of cross-section of the iron core inserted be called as usual the induction through the iron, then the quotient obtained by dividing the magneto-motive force of the helix by the induction gives the whole magnetic resistance of the magnetic circuit traversed by the lines of force. In a

bar electro-magnet, or in a horse-shoe, with the poles not touching, the magnetic circuit is partly of iron and partly of air, and hence the resistance is a joint effect depending on the permeability (which is the reciprocal of resistance) of the iron and of the air. As long as the iron is a good way from saturation, the induction through the iron, and hence the intensity of its magnetisation, is proportional approximately to the total magnetising power, or to the ampère-turns; hence the field just outside any such magnet is proportional to the same quantity. If a piece of soft iron is placed in this field, the intensity of its induced magnetism is approximately proportional to the strength of the field, and accordingly the attraction between this iron and the magnet, which is proportional to the product of the strengths of the inducing and induced poles is, within certain limits, proportional to the square of the strength of the exciting current, and proportional to the number of turns the wire round the electro-magnet makes. This is the result found by several experimentalists. The law, however, does not hold good, near to, and at, or beyond the point of saturation of the iron. The larger uses of electro-magnets in dynamo-electric machinery are confined to the production of as intense a magnetic field as possible. The electro-magnets in a dynamo machine, whose function it is to produce the magnetic field in which the bobbin revolves, are called the field magnets. Field magnets are made in many different forms. In some, such as the Edison dynamo, they take the form of round bars or legs, united by a square yoke, and having at the bottom massive pole pieces. (See Fig. 34.) In the earlier Edison machines, these legs were made rather long and thin, and the magnetic resistance offered by the circuit was too large. By adopting shorter and thicker legs, Dr. Hopkinson improved the machine and obtained a greater induction, or number of lines of force per square centimetre of cross section. In the best dynamos as now

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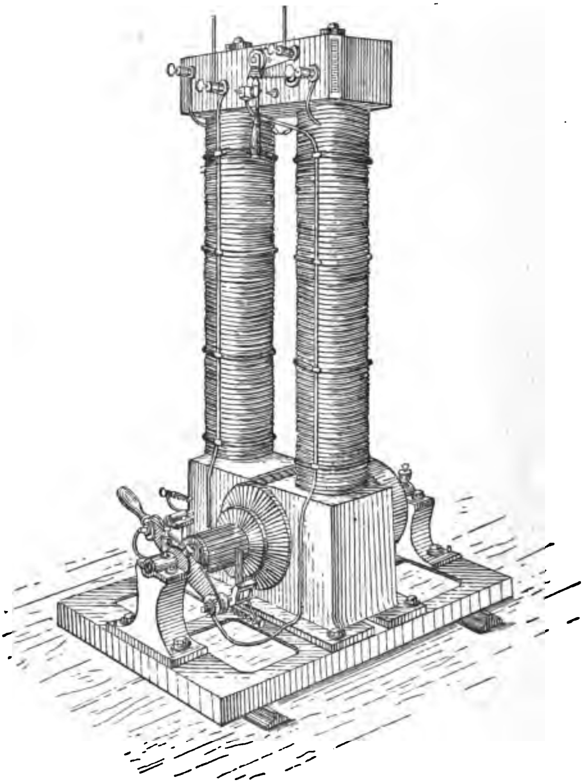
designed, the number of lines of force through the air gap is about 6000 to 10,000 per square centimetre. Various forms of field-magnets are figured in Fig. 35.

Fig. 34.



Edison Dynamo (old form).

The general form of field magnet adopted in Edison's dynamo machines, is that of a single horse-shoe magnet, with

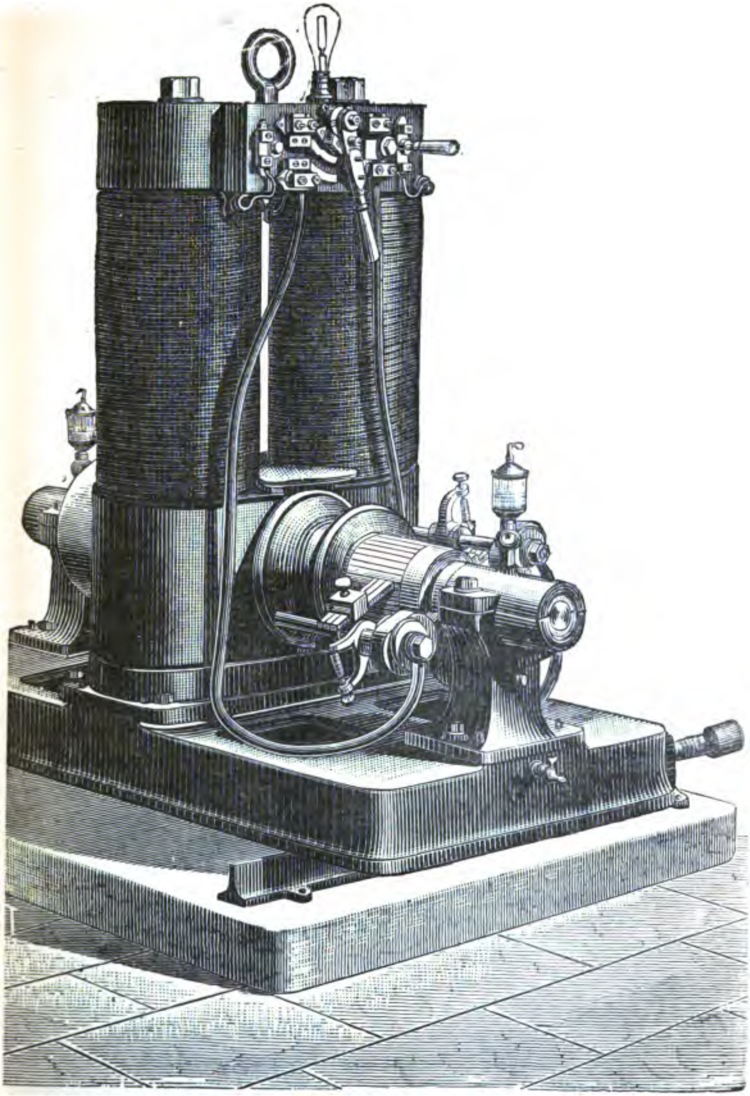


Fig. 34A. The Edison-Hopkinson Dynamo.

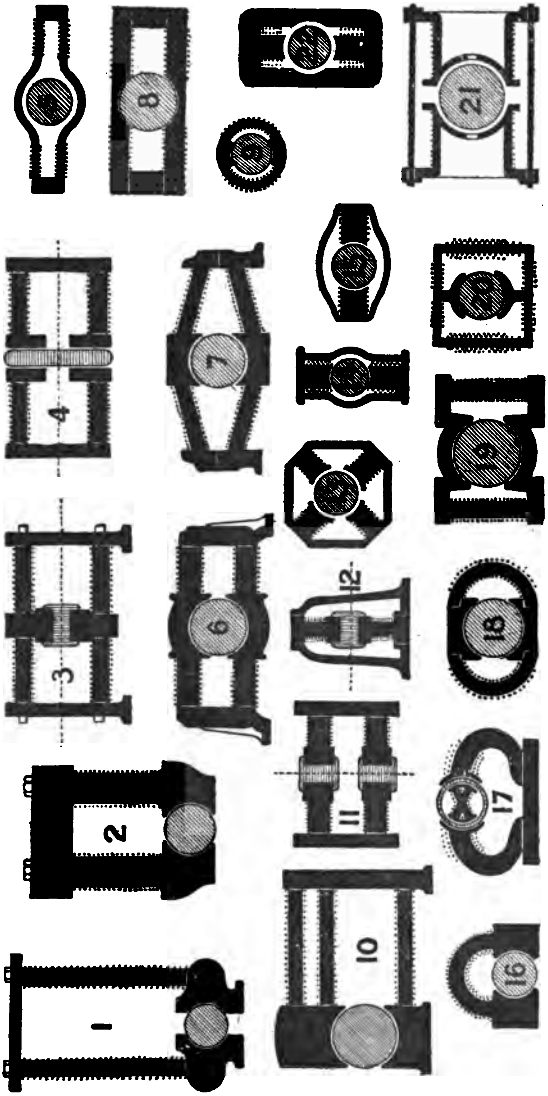
the poles downwards. (1, Fig. 35.) As it is necessary to bolt this down upon a bed-plate, which must be of iron, it is essential to insert a layer of non-magnetic metal, generally zinc, to prevent contact between the polar ends and the iron bed-plate, otherwise, a magnetic short circuiting would take place which would reduce the strength of the inter-polar field. In the form of field magnets adopted by Crompton and Siemens, there is a pair of horse-shoe magnets placed with poles against one another (6, Fig. 35), and there is therefore no such difficulty. In other cases, single magnets are placed with poles uppermost, with the object of altogether removing the pole pieces from the neighbourhood of the bed-plate. (17, Fig. 35.) In some cases, electro-magnets have been constructed with cores of cast iron, chiefly with the object of reducing expense.

The magnetic permeability of cast-iron appears to be very much less than that of wrought, and hence a given magnetising force of a certain number of ampère-turns per centimetre of length is less effectual in producing induction; that is to say, gives rise to a less number of lines of force per square centimetre of cross section.*

§ 34. If the coil of an electro-magnet is traversed by alternate or intermittent currents at every variation in the current strength, induction currents will be generated, which will circulate in the mass of the metal. The path of these

* Mr. G. Kapp has stated ('Electrician,' May 22, 1885, p. 23, vol. xv.) that he has tried by direct experiments on field magnets the relative value of cast and wrought-iron for cores. In one case, the same armature, designed to yield about 40 ampères, was excited by field magnets of the same size, in one case with wrought and in the other with cast-iron cores. To obtain 100 volts E.M.P. with cast-iron, the exciting power had to be more than doubled; and at the same exciting power the cast-iron fields only gave 80 volts, when the wrought-iron gave 100. The armature was a modified Gramme, with a smooth core. These experiments showed how inferior cast-iron cores are to wrought in the matter of permeability.

Fig. 35.



Various Forms of Field Magnets of Dynamos.

currents is in directions parallel to the coils of the exciting helix. These induction currents dissipate themselves in producting heat in the iron core. This heat represents so much energy abstracted from the magnetising current. If the continuity of the iron core is interrupted, so as to cut it up in such a direction that these currents cannot be formed in it, then there will not be this waste of energy. These currents which form in the iron core are often called the Foucault currents, or better, the eddy currents in the core. Foucault first gave an instance of their formation by rotating a copper disc rapidly between the poles of an electro-magnet. The disc became very hot. If a penny be suspended between the poles of a powerful electro-magnet by means of a twisted thread, when it is released, it commences to spin rapidly. If the electro-magnet be excited so that the penny is revolving in a strong magnetic field, it rapidly comes to rest. The reason for this is that the motion of the penny generates in it, under the influence of the magnetic field, induction eddy currents which are in such a direction as to oppose the motion. If the penny be forcibly twisted against this resistance, then the energy so expended has its equivalent in heat produced in the metal by these eddy currents.

Foucault showed that the forcible rotation of a highly conducting disc in a strong field can generate in it heat sufficient to bring it to a very high temperature. In all dynamo machines the armature, or revolving bobbin of wire, by which the current is generated, consists essentially of an iron core, wound over with covered copper wire, or with copper bars, and it revolves in a strong magnetic field. Such a core, if made of solid iron, would be almost immediately rendered hot enough to destroy the insulation of wire wound over it. It is necessary to construct this core in such a manner as to prevent the formation of these eddy currents. This is accomplished by making

the core of discs or sheets of thin iron, separated from each other by a layer of varnish or thin paper, or some non-conducting material. It may be also accomplished by constructing the core of iron wire rolled up, but in any case the planes or lines of division must be parallel to the lines of force of the field, because the induction tends to cause eddy currents directed at right angles to the field, and hence the subdivision of the iron must be so arranged as to defeat this, and render impossible any electric flow in the direction at right angles to the direction of the field.

In the instrument commonly called an induction coil, we have an arrangement which consists essentially of an electro-magnet, the wire of which (called the primary) is traversed by an intermittent or an alternate current. In order to avoid the production of eddy currents, the core, either straight or annular, is constructed of iron wires, or thin iron plates. These are oxidised or rusted on the surface by exposure to the fire, and this film of oxide is sufficient to form an obstacle to the production of currents across from wire to wire, whilst at the same time the continuity of the iron is preserved in the direction in which it is essential it should have the greatest possible magnetic permeability.

§ 35. An induction coil is an apparatus for obtaining induction or secondary currents in one wire, placed in the magnetic field of another wire traversed by a primary current, which is either interrupted or alternated in direction.

In Fig. 36 we have a sketch of the arrangements. I I′ is an iron wire core, composed of very well annealed soft iron wire, each wire slightly oxidised, and the whole tightly bound together. Over this is wound a primary wire P, or magnet wire. In the circuit of this is the battery B and a magnetic interruptor, consisting of a vibrating hammer armature H, the connections being so made that the instant the circuit is complete the attraction of the armature H to

the magnet I I′, breaks the circuit at the contact screw O, and therefore stops the current. The armature H springs back and then re-makes the current, and so, by a self-acting arrangement, the current in the primary circuit is interrupted many times in a second. Between the point of contact O and the hammer is inserted a condenser C C′. This consists of alternate sheets of tinfoil and paraffined mica.

Fig. 36.

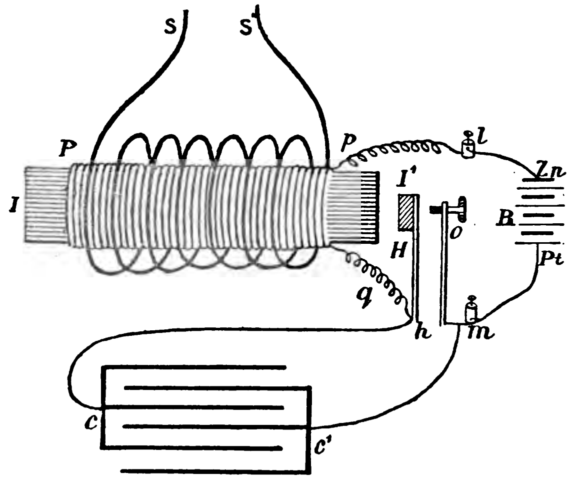


Diagram of Induction Coil Connections.

The alternate sheets of tinfoil are connected together on each side. This arrangement is useful in checking the spark at break of contact and apparently operates to increase the suddenness of interruption of the current. Over the primary is wound a coil of considerable length of fine wire, well insulated, S. This is the secondary. The secondary embraces the whole of the lines of force which the primary induces through the iron core, and at each

interruption of the current the whole of these lines are removed from the secondary, creating in it a powerful electromotive force. By this means, a current of a few ampères circulating in the primary under an electromotive force of not more than ten or twenty volts, can be caused to yield short currents in the secondary having an electromotive force of many thousand volts. According to De la Rue, the electromotive force required to jump across a distance of $\frac{1}{12}$th inch of air is about 8000 volts. A spark of 1 inch, easily obtained by a small induction coil, will indicate an electromotive force between the terminals of the secondary of some 32,000 volts. At each interruption of the primary such an electromotive force will be set up in the secondary, creating a discharge which will jump across an air space of considerable magnitude.*

Very great precautions as to insulation are essential, in order to obtain long sparks from induction coils. In a large coil, built for the late Mr. Spottiswoode, the secondary coil had a total length of about 280 miles, and the primary a total length of 1164 yards.

Mr. Spottiswoode obtained very powerful discharges from his coil by disconnecting the interruptor and condenser and sending direct into the primary the alternate currents of a De Meritens alternate current magneto-machine.

Induction coils, such as the above, formerly found their applications only in scientific research and experiments, but they have recently, with modifications, become important practical appliances in electric lighting, and in this application are called secondary generators.

§ 36. An induction coil is a reversible machine. If a current of considerable magnitude circulates under small

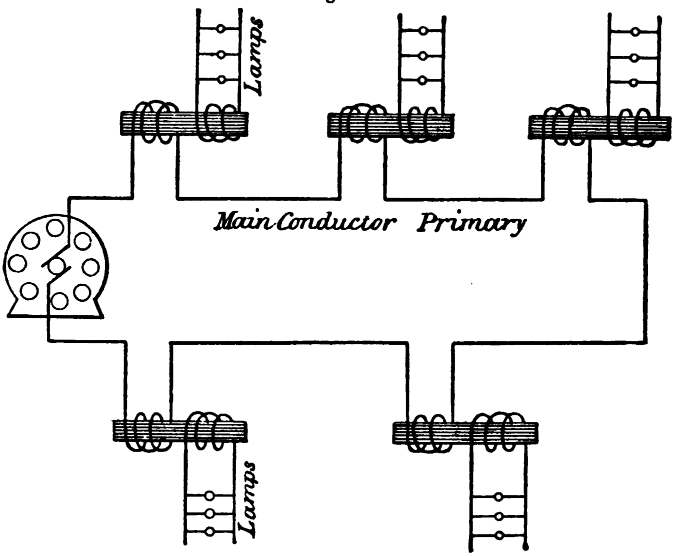
* De la Rue found that between pointed terminals in air an electromotive force of 1000 volts gave a discharge across ·005 in., and speaking generally, the length of striking distance varies roughly as the square of the electromotive force.

electromotive force in the primary, then variations in the strength of this give rise to very small currents of exceedingly high electromotive force in the secondary. We may reverse this operation, and cause to circulate in the secondary small currents under very high electromotive force. These, by their fluctuations, will generate in the primary large currents of small electromotive force. We do not, in either case, create electric energy. The energy of a current flowing in a conductor at any instant is measured by the product of the current strength and the electromotive force between the ends of that conductor, and hence electric energy is a quantity which is the product of two factors, current and electromotive force. What the induction coil enables us to do is to increase one of these factors at the expense of the other, and transform our electric energy in form, but not in amount. In this respect we operate on electric energy by means of an induction coil, just as a simple mechanical power, such as a pulley, enables us to operate upon mechanical energy, converting a quantity of work which consists of a small stress exerted through a great distance into a large stress exerted through a small distance.

Now in the distribution of electricity under low electromotive force, one difficulty, as we shall see later on, which presents itself, is the size of the conductors required to transmit large currents to great distances. By the use of secondary generators we can convert our large currents of low electromotive force into small currents of high electromotive force, and so convey the electricity at a reduced cost of conductor. There are at present several different forms of secondary generators in use. Some inventors have preferred to use a straight core of iron wire, and to wind this over with two insulated circuits, one to convey the small primary current and the other to have induced in it the large secondary current, utilised for lighting purposes. Such generators may be arranged in series (see Fig. 37), the same primary current passed through

all of them, and from each secondary circuit leads taken off to work local lights. But they may be arranged to work in parallel (Fig. 38), in which case each primary current is a bridge across from main to main of the alternate current

Fig. 37.

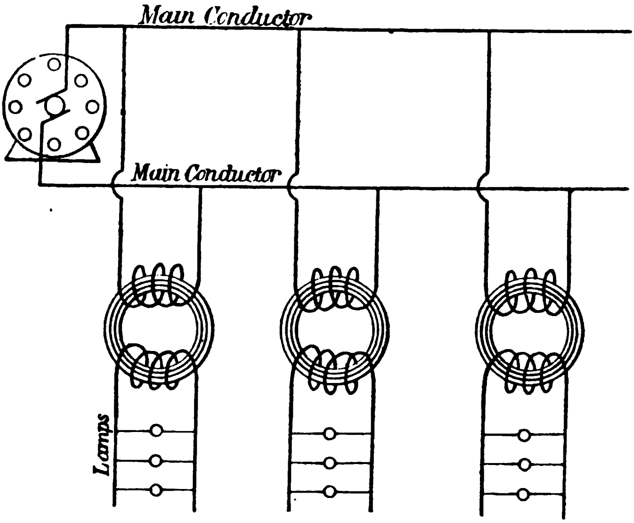


Arrangement of Secondary Generators with Primary Coils in Series.

machine which supplies the alternating current of high electromotive force. In both cases, however, the secondary current would, if used for lighting ordinary incandescent lamps, be led through the lamps in parallel. Other inventors have recognised the important fact, that the best results will be obtained if the iron core of the secondary generator is continuous, so that there are no free poles, and Dr. Hopkinson, MM. Zipernowski, Deri, and Mr. Ferranti have devised forms which comply with these conditions.

In Hopkinson's transformer, the core is formed of iron wire, after the manner of a Gramme ring, and wound over with two insulated wires, a thin primary and a thick secondary. The simple ring form of induction coil was amongst the

Fig. 38.



Arrangement of Secondary Generators with Primary Coils in Parallel.

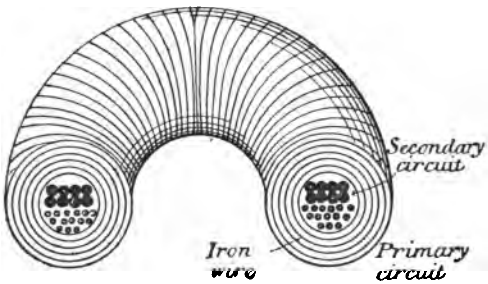
earliest of Faraday's experiments on induction. He provided a solid wrought-iron ring and wound it over with two wires so that it formed a poleless electro-magnet with double wire. One wire was then connected to a battery and the other to a galvanometer. At each make and break of contact on the battery circuit, the iron ring was magnetised and de-magnetised, and this powerful induction acting on the other circuit generated induction currents of considerable magnitude. In Faraday's arrangement the ring was of solid iron, and

hence for reasons above given was subject to the formation in its mass of eddy currents. If the ring were submitted to rapid reversals of polarity these eddy currents would generate in it a considerable amount of heat. By forming the ring of thin iron wire coiled up, the formation of these eddy currents is hindered, whilst at the same time the continuity of the iron is preserved along the ring, and high permeability thus preserved in the direction in which it is necessary to keep it. In Zipernowski's form of transformer the position of iron and copper is inverted. If we imagine a circular primary current laid on to, but insulated from an equal sized circular secondary circuit, it will easily be seen that the lines of force from the primary all embrace and pass through the secondary. The magnetic resistance of the air imposes a limit upon the induction which a given magneto-motive force can produce. If, however, the two circular conductors lying together are lapped over with iron wire, the greater permeability of the material now lying round about the circuits enhances the induction greatly, and increases the effect of the apparatus as a transformer. A little thought will make it evident that the iron is continuous, just in the direction of the embracing system of lines of force of the circular currents, but interrupted in the direction in which wasteful eddy currents endeavour to flow at each change of strength of primary, and hence results an effective form of transformer for producing low pressure alternate currents from equivalent high pressure.

Zipernowski's transformer resembles in shape a life-buoy or air-cushion. (Fig. 39.) The primary and secondary copper conductors lie in the central axis of the core, and are wrapped over with iron wire to as great a thickness as is possible, having regard to the size of the ring. The iron then forms a closed magnetic circuit for the circular field of force, surrounding the primary wire, and the field in which the secondary wire lies is thus greatly intensified. The primary

coils of many generators or transformers are joined in parallel between two mains leading from an alternate current dynamo of high electromotive force, about one to two thousand volts, and from each secondary circuit wires are taken off to a local lamp system.

Fig. 39.



Section of Ring-shaped Secondary Generator of Zipernowski-Deri.

At each reversal of the primary current, a secondary induction current of low electromotive force is generated in each transformer, and is utilised in the lamps attached to it.

LECTURE V.

§ 37. It will be essential to preface a detailed account of the construction of electrical measuring instruments by a short sketch of the system of electrical weights and measures, which has now, since the Paris Congress of Electricians, obtained universal acceptance. Everything, which has the property of being more or less, and which can have its how-much-ness expressed exactly by comparison with something of the same kind, is called a physical quantity. Thus, for instance, the volume or weight of a body is a physical quantity, and is expressed by saying how many times or fractions of a gallon or cubic inch, pound, or gramme amount to the same. In this case the pound or the gallon are called the units or standands of comparison, and the number or numeric, expressing the relation of the given thing to the units in respect of the quality considered, is called its *magnitude*. Many things can be more or less, which are not, however, physical quantities. For example, a sensation of heat or cold can be more or less; but in so much as we cannot compare its amount definitely with a unit sensation, it follows that a sensation of heat is not a physical quantity or magnitude. The first thing in arranging a system of measurement is to select the units or standards with which any given magnitude is to be compared. We might begin by selecting quite arbitrarily a certain length, a certain time, a certain volume, a certain force, &c., to be our units, and these might be so taken that there was no definite simple relation between them. Such a system imposes a great waste of brain labour in performing the

simplest calculation, and the ordinary British system of weights and measures seems to comply with the condition of creating the utmost possible waste of brain labour in performing the simplest calculation. There being no simple relation between the pound and cubic inch, the operation of finding the weight of a given volume of iron or water necessitates the employment of several constants or numbers which must be at hand, in order to perform this simple calculation. A system of weights and measures in which every unit quantity is related in the most simple way to the fundamental units of length, mass, and time, is called an absolute system. The term absolute is not well chosen. It might better be called a simply-related system. In the metric or French system, the units of length and mass are also brought into relation with each other in the most simple manner.

The founders of the French metric system started with the notion of taking as the unit of length a decimal fraction of some natural magnitude, such as the length of the earth's meridianal quadrant. As, however, subsequent progress in geodesy has indicated that the measurement Delambre and Mechin completed in 1799, of the meridianal arc, was in error by defect, it follows that, if the subsequent deductions of Bessel and Airy be correct, the metre, as settled by the French Government in 1801, is less than one ten-millionth of the earth's meridianal quadrant. For all practical purposes it might just as well have been any arbitrary length. The value of the metric system does not rest in the natural magnitude of the unit of length, but in the simple relations of the various units to one another. On the 2nd November, 1801, the French Government defined the unit of length to be the distance at 0° C. between two points on a platinum bar in the keeping of the Academy of Science at Paris. This standard bar is preserved with the most jealous care, being only used very occasionally for comparisons with

other units. This distance is called one metre, and is equal to 39·37079 English standard inches. Fractions or multiples of a metre are expressed as one word by putting a Latin or Greek prefix, as follows:—

Prefix.		Signification.
Micro-	means	One millionth of a —.
Milli-	„	One thousandth of a —.
Centi-	„	One hundredth of a —.
Deci-	„	One tenth of a —.
Deka-	„	Ten times a —.
Hecto-	„	Hundred times a —.
Kilo-	„	Thousand times a —.
Myria-	„	Ten thousand times a —.
Mega-	„	One million times a —.

Usual abbreviations are cm. for centimetre; sq. cm. for square centimetre; cub. cm. for cubic centimetre; mm. for millimetre.

Thus a centimetre is one hundredth of a metre, or ·3937079 inch, and a kilometre is a thousand metres or 39370·79 inches. In round numbers a metre is three feet three inches and three-eighths of an inch. One or two numbers are constantly required. They are as follows:—

One foot ..	=	30·4797 centimetres, and reciprocally.
One centimetre	=	·0328087 of a foot.
One inch ..	=	2·500 centimetres.

The basis of the electrical system of units is the selection of a fundamental unit of length. The centimetre is taken as the unit of length. In expressing large numbers it is convenient to indicate cyphers in the following way: 10^6 stands for 1 followed by 6 cyphers, or for one million; 10^9 stands for 1 followed by 9 cyphers, or a thousand millions, and so on. The earth's circumference measured round the poles, is approximately 40^9 centimetres, or four thousand million centimetres. The unit of square measure

is the square centimetre, and the unit of cubic measure is the cubic centimetre, being respectively a square and a cube whose sides are 1 cm. One thousand cubic centimetres is called one litre.

One square inch	=	6·4516 sq. cm., and
One cubic inch	=	16·387 cub. cm.
One gallon ..	=	4541 cub. cm.

Having settled our unit of volume, the unit of substance or mass is derived from it thus. Fill a cubic centimetre of volume with pure distilled water at 4° centigrade. The mass of this is called one gramme, and is taken as the unit of mass.

One British standard pound avoirdupois	=	453·59 grammes.
One ounce avoirdupois	=	28·3495 grms.
One kilogramme	=	2·2 lbs. nearly.

The advantage of establishing this relation between bulk and mass is that the mass, or what is commonly called the weight, of water contained in any vessel is at once deduced from its cubic contents in cubic centimetres. The fundamental units are completed by taking for the unit of time the mean solar second. These three units, the centimetre, the gramme, and the second, form the basis of the system called the C.G.S. system of weights and measures. The time during which the earth makes one complete revolution round its axis, is called a sidereal day, and a mean solar second is the time of one swing (from side to side not backwards *and* forwards) of a pendulum, which makes 86164·09 swings in a sidereal day, or 86400 swings in a mean solar day. The units of length, mass and time, being determined, everything else is built up from these fundamental units. The principal derived units are those of *velocity*, *acceleration*, *momentum*, *force*, *energy*, and *activity*. They are defined

as follows: If a small body, so small that we may consider it as a material point, moves in space, it must do so along a certain path. Select two points on its path very close together, and observe the interval of time in which it passes from one to the other. The small distance of these points being measured in fractions of a centimetre, and this number divided by the time in fractions of a second taken to traverse the little interval gives the numerical value of the mean velocity during that interval. Velocity is defined as rate of change of position along any path, and the unit of velocity or speed is one centimetre per second. Uniform velocity is uniform change of position or speed. If the velocity is not uniform, there will be not only a change of place, but a change of speed. Rate of change of speed is called acceleration, and the unit of acceleration is a change of speed of one centimetre per second. When a body falls under the action of gravity, its speed continually increases, and the rate of increase is an addition of 980 centimetres per second added every second. So that whereas the speed at the end of one second is 980 cm. per second, at the end of two seconds it is 1960 cm. per second, and at the end of three seconds it is 2940 cm. per second. *Acceleration* is related to *velocity*, just as the last is related to position. Velocity is the time rate of change of position, and acceleration is the time rate of change of velocity. Acceleration is called positive when velocity is increasing, and negative when velocity is being diminished.

The fundamental property of matter is, that it cannot accelerate itself. If it is accelerated it must be due to some external cause. The inability of matter to accelerate itself is called inertia. That which causes acceleration is called force. It is an experimental fact that a given force produces very different accelerations when it operates upon equal bulks of different kinds of stuff; but it is always possible to find quantities of different kinds of matter such, that when

subjected to the same force, they have their velocities changed at equal rates; in other words, are dynamically equivalent. Such relative quantities of matter are called *equal masses*. If a body be divided up into masses, each equal to the mass of one cubic centimetre of water, then the number of such units expresses what is called its mass.

A force is therefore measured dynamically by the acceleration it can cause in a unit mass, or the velocity it can communicate to a unit mass, viz. one gramme after acting upon it for one second. The unit of force is called *one dyne*. One dyne acting for one second on one gramme increases or diminishes its velocity by one centimetre per second in the direction in which it acts.

If a mass of one pound is let fall under the action of gravity at London, at the end of one second its velocity is 981 cm. per second. Hence the so-called "weight of one pound" at London is a force of $453 \cdot 59 \times 981$ dynes $= 4 \cdot 45 \times 10^5$ dynes, or about half-a-million dynes.

The product obtained by multiplying together the number representing the mass of a body and its velocity at any instant gives us what is called its *momentum*. The rate at which a body's momentum is being changed at any instant in any given direction is a measure of the force acting on it in that direction. It is essential to note that in all these cases where we are dealing with quantities like velocities, accelerations, &c., which have direction as well as magnitude, that the word *change* is to be taken as meaning either in direction, or in magnitude, or in both. Thus, a body moving uniformly round in a circle is being accelerated, because its velocity is continually being changed in direction, though not in numerical amount. A quantity which has, like velocity, direction as well as magnitude, is called a *vector* quantity. Other quantities, like mass, are called *scalar*, or directionless quantities. The next dynamical notion is that of *work*. If a body is acted upon by any

force, and it is displaced or moved in the opposite direction to that in which the force if allowed to act freely could move it, this is called making a displacement in opposition to a stress. Thus, for instance, if a weight is lifted the motion is made to take place in opposition to the stress of gravity. Now, whenever this is the case, work is said to be done against the force, and the work is numerically measured by the product of the displacement, and the mean stress estimated in the direction of the displacement. Energy is a capacity for doing work, and when work is done energy is said to be expended. Energy exists in many different forms. The energy of a bent spring is of a different form to that of a moving heavy body, and both of these are different to the form of energy represented by an electric current. Nevertheless, these forms of energy are found to be transmutable, and are capable of being exchanged for their equivalents in that form of energy expenditure represented by a definite mass lifted up to a certain height against gravity, or a displacement through a certain distance made against a certain stress or force measured in dynes. Hence if feet and "pounds' weight" be our units of length and stress, one foot-pound, or one pound mass lifted up one foot against gravity, represents a certain quantity of work done and a certain amount of energy expended. In the C.G.S. system a displacement of one centimetre against a force of one dyne is the unit of work, and is called one *erg*. Now since, as we have seen, the force of gravity acting on a mass of one gramme at London is 981 dynes, it follows that if a gramme is lifted up one centimetre, an amount of work equal to 981 ergs is done, and one foot-pound is equal to $1 \cdot 356 \times 10^7$ ergs, or to 13,560,000 ergs. An amount of work equal to 10 million ergs is called one *joule*. Hence one foot-pound $= 1 \cdot 356$ *joules*, or one *joule* $= \cdot 7373$ foot-pound. The elaborate researches of Mr. Joule, after whom this practical unit is called, have shown that the amount of heat required

to raise one gramme of water one degree centigrade in temperature is equal to 4·2 joules, or to 42 million ergs, or 3·096 foot-pounds. This number is called the mechanical equivalent of heat, and it represents the amount of work required to be done in order to increase the motion of the molecules of a gramme of water by an amount equivalent to heating that quantity of water one degree centigrade.

The value which attaches as a work doing agent to any energetic body, whether man, horse, steam-engine, or to any store of energy, is the rate at which such agent or store can deliver energy, or the work it can do per second. The work done per second by any agent is called its *activity* or power, and the unit of activity is a rate of working of one erg per second. As the rate is excessively small, the practical unit adopted is a multiple of this, equal to 10 million ergs per second, and is called *one watt*. Common usage still retains as a unit of activity or power, the horse-power, which is a rate of working of 550 foot-pounds per second, or 33,000 foot-pounds per minute. One horse-power is equal to 746 watts.

We may connect all the above dynamical notions together by noticing the following relations between them. Let us suppose a very small heavy body to be set in motion, such as a small shot falling through the air. On its path take two positions so near that the body takes a very short time to pass from one to the other. The distance of these two points in fractions of a centimetre divided by the time taken to pass from one to the other in fractions of a second, gives the mean speed or velocity in C.G.S. measure during that interval. Hence velocity is the time rate of change of position.

Let us suppose we take two points on its path, such that the velocities at those two points differ by a very small amount, and note the time taken to produce this small increase in the

velocity. The quotient of the small increase in velocity by the time occupied in making it is called the mean acceleration during the interval, and hence acceleration is measured by the time rate of change of velocity. In the case of a body falling under the action of gravity, this time increase of velocity will be at the rate of 981 centimetres per second, added per second.

Next take the product of the mass of the body measured in grammes, and its velocity at any instant. This gives us the momentum. Take two points on the path, such that the momentum at one is very slightly greater than that at the other. Divide the small increase of momentum by the time taken to produce this increase, the result is the measure of the mean force acting on the body during that interval. Hence force is measured by the time rate of change of momentum estimated in the direction of that force.

Lastly, if the energy contained in the moving body * is measured at any two points in its path very near together, and divided by the time occupied in making this change of energy, the quotient is the time rate of change of energy, or the activity spent on the body. If the energy decreases with time, then the activity is positive, or is the result of work done by the body; if on the contrary the energy of the body increases with time, its activity is negative and work is being spent on the body. Hence all these quantities, viz. velocity, acceleration, force, and activity, are of the nature of *rates*. They are the measures of changes of certain other measureable quantities.

§ 38. We now pass to consider the magnetic and electric units in relation to these fundamental ones. In measuring the strength of a magnetic pole, we might select arbitrarily a magnetic pole for the unit and compare others with it; but in the absolute system it is necessary to connect the

* The energy of motion of a moving body is measured by the product of its mass and half the square of its velocity.

strength of the unit pole with the fundamental units. It is done in the following way. Let a very long thin magnet be taken and broken in the middle. The broken ends develop two opposite poles of equal strength. If the magnetic filament is very long and thin, these poles will be very near the extremities. Suppose these poles held one centimetre from the other, and let the attraction between them be measured in dynes. This might be done by a very delicate spring balance, or torsion balance. If these poles are of such strength that at a distance of one centimetre they attract each other with a force of one dyne, they are said to be of unit strength.* The strength of a magnetic pole is measured by the number of unit poles to which it is magnetically equivalent, and hence the strength of a magnetic pole is reduced to a measurement of distances and dynes. If a unit magnetic pole is held in a magnetic field, and if we suppose the magnet to be so long that the other opposite pole is removed altogether away from the field, then, as we have seen, there is a force impelling the magnetic pole to move along the lines of force of the field. This force measured in dynes is a measure of the strength of the field, and a unit field is one which acts on a unit pole with a force of one dyne. The C.G.S. unit field is rather a small unit and it would be convenient if the name of "one gauss" were applied to the strength of a field of 100 C.G.S. units.†

The unit of current is obtained by the consideration that

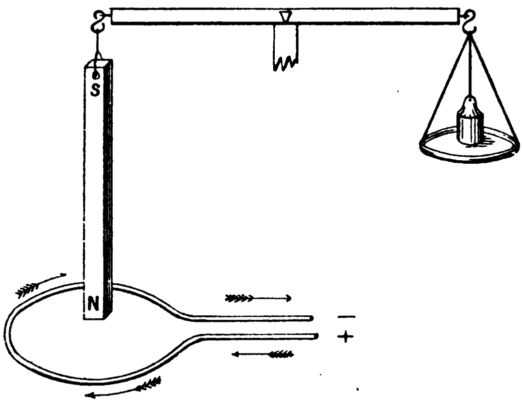
* Practically speaking two opposite poles slightly strengthen each other, and two similar magnetic poles slightly weaken each other when held near. In the above we must suppose this source of error to be allowed for.

† Prof. S. P. Thompson, in his 'Treatise on Dynamo-Electric Machinery,' suggested the term "gauss" to signify a field strength of 100 million C.G.S. units. As the strongest dynamo fields are only about 10,000 C.G.S. units it would be convenient to have the term one gauss applied to a lesser multiple of the C.G.S. unit field.

the electro-magnetic force, with which a current acts upon a magnetic pole, is proportional to the product of the strength of the pole and the strength of the currents.

Let us suppose (see Fig. 40) a thin wire is bent into a circle of unit radius, that is to say, of two centimetres in diameter, and a magnetic pole of unit strength held at its

Fig. 40.



Weighing the Attraction of a Magnetic Pole and a Circular Current.

centre, the other pole being removed out of the field by using a long magnet. Let the force with which a current flowing in this circular wire acts on the unit pole be measured in dynes. This can be done by weighing the attraction or repulsion in grammes weight and multiplying by 981.

Then since the length of the circular current of 1 cm. radius is 6·283 cms., the attraction of a unit length of the circular current of unit radius is obtained by dividing the attraction in dynes by the number 6·283. This gives us the attraction or the force in dynes with which a unit

length of a current acts on a unit pole when each part of the conductor is at a unit distance from the pole. If such a current is passed through the wire that this force is equal to one dyne, the current is called a unit current. Hence a unit C.G.S. current on the electro-magnetic system is defined to be a current such that unit length of it acts on unit magnetic pole with unit force, every point of the current being at unit distance from the pole. One tenth of this C.G.S. unit current is called *one ampère.*

The ampère is therefore the name for a certain rate of delivery of electricity, or of a certain strength of flow. We have not in hydro-dynamics adopted any particular name for a gallon a minute, but there is a necessity in electricity for a short single name to denote the corresponding idea. The quantity of electricity conveyed by *one ampère* per second is called *one coulomb.* Hence a coulomb is ultimately based upon the fundamental dynamical units of length, mass, and time.

When water flows from one place to another it does so in virtue of a difference of pressure between the two places, and the flow takes place *from* the place of high pressure *to* the place of low pressure.

Thus, for instance, when water flows down from a cistern this pressure, at any point in the pipe, is due to the "head" of water above it. If it is set flowing by a pump or turbine we might call this a water-motive force, and say the flow of the water was due to a water-motive force which could be expressed as equal to a "head" of so many feet of water. Exactly in the same way electricity flows in a wire or conductor only when there is a difference of electrical pressure between its ends. This difference of electrical level is called difference of potential, and difference of potential in electricity is exactly analogous to "head" of water in hydrostatics. The difference of electrical level or potential must be caused by some electromotive force acting in

the conductor. This electromotive force may be due to contact of chemically dissimilar substances, or to movement of part of the conductor in a magnetic field; but however caused it is measured by the difference of electrical level or potential it can produce.

In any case we may say that difference of potential for electricity is analogous to difference of level for water, and that electricity always tends to flow from places of high potential to places of low, and the criterion of difference of potential between two places, or points, or bodies is, that if these bodies are joined by a conductor electricity will flow along it. Now, this being the case, it follows that if electricity is made to move in opposition to a difference of potential, or to electromotive force, or is, so to speak, carried uphill, we are making a displacement of electricity against electric stress, and experience shows that this requires an expenditure of energy, and that electricity cannot be carried against electromotive force without doing work and drawing upon a supply of energy of some form. Difference of potential is therefore measured by the work done in conveying a unit quantity of electricity against it or in opposition to it. The C.G.S. unit of difference of potential is that amount of difference of electrical condition, such that if a C.G.S. unit of quantity of electricity be carried against it, one erg of work is done. This unit of difference of potential is too small for practice, and a multiple of it equal to 100,000,000 times is selected for the practical unit and called *one volt*, and is so chosen that one coulomb of electricity conveyed against a difference of potential of one volt, requires an expenditure of one joule; so that one joule = one volt-coulomb. That is to say, if a coulomb of electricity flows down between two points in a conductor whose difference of potential is one volt, then one joule of work is done thereby. Hence it follows that if a conductor is traversed by a current of one ampère and we find on it two points whose

difference of electrical level is one volt, then the rate at which energy is being expended in that portion, or the activity in this portion of the conductor, is one watt.

In every case in which a steady electric current flows in a conductor, it is found that when any two points on the conductor are taken, and the difference of potential between these two points measured, the numerical value of this difference of potential measured in volts, divided by the numerical value of the current in ampères, gives a quotient which is entirely independent of the strength of the current. Hence, if the flow be doubled, the difference of potential is doubled, and if the current strength be halved the difference of potential is halved. This constant ratio of electric pressure to electric flow is called the electrical resistance of the conductor. The difference of potential between any two points in a conductor may be called the electric pressure between these points, and the strength of the current may be called shortly the electric flow. Hence

$$\text{Resistance} = \text{pressure} \div \text{flow.}$$

If pressure be measured in volts, and flow in ampères, the resistance of a conductor in which a differential pressure of one volt produces a flow of one ampère, is called *one ohm*, and we have

$$\text{Pressure in volts} \div \text{flow in ampères} = \text{resistance in ohms};$$

or divide the difference of pressure between any two points by the current flow in ampères, and we get the resistance in ohms.

Elaborate experiments performed by Prof. Chrystal, under the guidance of Prof. Clerk Maxwell, have shown that for solid conductors the electrical resistance is a quantity which depends only on the dimensions and shape of the conductor, and on the nature of the material of which it is made, but

not on the strength of the current passing through it, assuming always a steady current and a uniform distribution over the cross section of this conductor.

The resistance of a cubic centimetre of any substance to a current passing between opposed places is called the *specific resistance* of the substance.

The resistance of a conductor varies as its length, and inversely as the area of its cross section. Hence, if its specific resistance is given in ohms, all that has to be done to obtain the resistance of a wire or rod is to multiply this specific resistance by the length in centimetres, and divide by the area of cross section in square centimetres. If the resistance of a pure copper wire of a certain length and diameter is given, then it is frequently necessary to know the resistance of wires of other metals of the same size. This may be done by the help of the following rule. Given the resistance of a copper wire of pure copper, to find approximately the resistance of an equal sized wire of the following metals :—

For *Brass*,	multiply copper	resistance by	4·5
„ *German silver*,	„	„	12·9
„ *Iron*,	„	„	5·9
„ *Platinoid*,	„	„	19·5
„ *Platinum-silver alloy*,		„	14·8

We derived our definition of a volt just now from the consideration of the quantity of work performed in lifting a coulomb of electricity through a certain difference of potential, or against a certain electromotive force. We might have arrived at it better from an electro-magnetic definition. If a conductor of unit length, viz. 1 cm., move in a magnetic field of unit strength perpendicularly to the lines of forces, then the electromotive force set up in it is proportional to, and measured by, the velocity with

which it moves. If it moves with a velocity of one centimetre per second perpendicular to its own direction and to that of the lines of force, then the E.M.F. set up in it is called one C.G.S. unit; 100,000,000 such units make one volt, or one volt = 10^8 C.G.S. units. If we imagine this electromotive force to set up a current of unit strength in the conductors in C.G.S. measure, which will be the case if the conductor has its circuit completed through a certain resistance; then it follows that the whole resistance of this circuit is numerically equal to the electromotive force, and this again under the supposition is numerically equal to the velocity of the conductor, hence we see a resistance is measured by a certain velocity: the velocity corresponding to one ohm is one thousand million centimetres per second. Thus we may speak of a resistance generally as a velocity, meaning that its absolute measurement reduces to the measurement of a velocity, just as the absolute measurement of a magnetic pole strength reduces to the measurement of a force, and a distance. Since the length of a meridianal quadrant of the earth is 10^9 centimetres, a resistance of one ohm is sometimes spoken of as a velocity of an earth-quadrant per second.

One other fundamental electrical unit remains to be defined, viz. that of *capacity*. If an insulated conductor, such as a submarine cable, has electricity put into it, its electrical potential rises. When it has risen to one volt above that of the earth, the quantity of electricity in it, measured in coulombs, is a measure of what is called its capacity.

The practical unit of capacity is one farad. It is defined to be the capacity of a conductor which holds one coulomb when charged to the potential of one volt.

§ 39. We may collect and summarise the practical electrical units, based on the electro-magnetic system, as follows:—

SUMMARY AND MEMORANDA ON ELECTRICAL UNITS FOR PRACTICAL USE.

MEMORABLE SCIENTIFIC NAMES.

Englishmen.	*Frenchmen.*	*Germans.*	*Italian.*
James Watt.	Charles A. Coulomb.	G. S. Ohm.	Volta.
Michael Faraday.	Andre M. Ampère.	Carl F. Gauss.	
James P. Joule.			

Names of Practical Electrical Units called after the above.

Force,	1 Dyne.	*Quantity,*	1 Coulomb.	*Resistance,*	1 Ohm.
Work,	1 Joule.	*Current,*	1 Ampère.	*Pressure,*	1 Volt.
Activity,	1 Watt.	*Capacity,*	1 Farad.	*Magnetic Field,*	1 Gauss.

These practical units are decimal multiples or fractions of the absolute units based on the centimetre, gramme, and second, and called the C.G.S. system. The absolute unit of current is 10 ampères. The absolute unit of E.M.F. is one hundred millionth of a volt. The absolute unit of resistance is one thousand millionth of an ohm. Prefix "mega" = 1 one million times; "micro" = one millionth part.

FUNDAMENTAL UNITS.

1 *Gramme.*	453·59 grms. = 1 lb. avoirdupois.
1 *Centimetre.*	30·4797 cms. = 1 foot.
1 *Second.*	86400 secs. = 1 mean solar day.

Unit Velocity = 1 centimetre per second.

FORCE.

Force is that which changes a body's state of rest or motion, or tends to move it.

Force is measured at any instant by the rate at which it is changing momentum either in direction or amount.

The unit of force is 1 *dyne.* It creates a velocity of 1 centim. per second in mass of 1 grm. after acting uniformly on it for 1 second.

Force of gravity = 980 dynes approximately.

Atmospheric pressure = 1 megadyne per square centim.

Work *or* Energy.

Work is done when any change of size or shape or position of a body is made in opposition to a force resisting such change.

Work is measured by the product of the average resistance and displacement.

Unit of work = 1 erg = 1 dyne overcome through 1 centim.

10 million ergs = 1 joule = ·7373 foot-pounds.

1 Board-of-Trade unit = 3,600,000 joules = 1·34 horse-power hour.

1 joule = 1 coulomb-volt.

4·2 joules = 1 calorie = energy in that amount of heat required to raise 1 gramme of water 1 degree centigrade.

Activity *or* Power.

Activity is the rate of doing work.

The unit of activity is 1 erg per second.

10 million ergs per second = 1 watt.

746 watts = 1 horse-power = 550 ft.-lbs. per second.

1 watt = 1 joule per second.

1 watt = 1 ampère-volt.

Current *and* Quantity.

Current strength in a conductor is quantity of electricity which flows past any point per second.

Practical unit of current = 1 ampère = 1 coulomb per second.

1 milliampère = one thousandth of an ampère.

1 ampère current deposits 4·025 grms. of silver, or 1·1739 grm. of copper per hour.

In any portion of a circuit the current in ampères multiplied by resistance in ohms gives fall in volts along that portion.

Electromotive Force *or* E.M.F.

Pressure of 1 volt forces a current of 1 ampère through 1 ohm.

The electromotive force between the brushes of dynamo, multiplied by ampère-current coming out, gives the *external activity* in watts.

Watts divided by 746 is commonly called electrical horse-power.

E.M.F. of Clark's cell = 1·435 true volts; decreases ·08 per cent. per degree.

Resistance.

1 Brit. Assoc. Unit = ·9868 true ohm.

1 Legal ohm (L.O.) = 1·0112 B.A.U.

1 L.O. = resistance of 106 centim. pure mercury 1 square millim. in section.

Electrical resistance of copper increases ·388 per cent. per degree centigrade.

Horse-power wasted in any conductor = square of "fall in volts" divided by 746 times "resistance in ohms."

Capacity.

1 Farad is capacity of conductor which holds one coulomb when charged with pressure of one volt.

Magnetic Field.

1 Gauss is strength of field in which a length of one million centims. of wire moving across the lines with unit velocity develops 1 volt of E.M.F. = 100 times strength of 1 C.G.S. field.

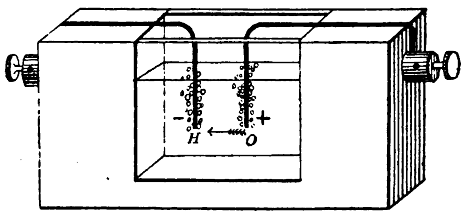
LECTURE VI.

§ 40. Presuming that the remarks in the previous lecture have been sufficient to illustrate in outline so much of the absolute system of electric measurement as is necessary for practical purposes in electric engineering, we can now address our attention to the consideration of the practical methods and instruments for measuring the quantities which we have seen are required to be known. Consider first the measurement of *quantity* of electricity. We have seen that when a current flows in a conductor, the quantity of electricity that has from the beginning of any time passed through it is measured in coulombs. An instrument for measuring quantity of electricity is, therefore, called a coulomb-meter, or simply a quantity meter. The simplest quantity meter is based on electro-chemical decomposition.

As early as the beginning of this century, Nicholson and Carlisle had performed the experiment of decomposing ordinary water by means of an electric current. Subsequent researches have, however, shown that pure water is not capable of being affected by a current of electricity. There are, however, a very large number of liquids known which are called *electrolytes*, which the electric current can decompose and bring out from them certain constituent elements called the *ions*. The largest class of electrolytes consists of solutions in water of either metallic salts, or of solutions in water of bodies called acids. If to water we add one-tenth of its volume of oil of vitriol or sulphuric acid, the resulting solution forms an electrolyte easily decomposed. In order that you may see for yourselves exactly the opera-

tions on a large scale, I place in the lantern a glass cell. This cell is filled with 1 to 10 dilute sulphuric acid, and into this liquid is dipped a pair of platinum wires. (See Fig. 41.)

Fig. 41.



Lantern Voltameter for Electrolytic Decomposition.

This arrangement is called a voltameter. We can connect at pleasure these platinum wires *H.O.* with a couple of small cells of a secondary battery. We project the image of the cell upon the screen and pass the current through the liquid. The platinum wires (called the electrodes) become at once crusted with the bubbles of gas. These bubbles are bubbles of oxygen and hydrogen gas which result from the decomposition of the dilute sulphuric acid. The wire at which the current enters the liquid is called the anode or positive electrode, or + pole, and the other one the kathode or negative electrode. The current travels through the electrolyte from + pole to − pole, and carries with it the hydrogen, liberating it at the − pole, whilst the oxygen is carried against the current and liberated at the + pole. Exact experiment shows that for every one cubic centimetre of oxygen evolved there are two cubic centimetres of hydrogen. Or by weight, that from every 1 gramme of hydrogen there will be 8 grammes of oxygen liberated from the electrolyte.

Faraday was guided by careful investigation to the conclusion that, when a current flows, as in this case, through

dilute sulphuric acid, the amount or weight of electrolyte decomposed is exactly proportional to the quantity of the electricity that has traversed it. Hence if we, for instance, catch and measure the bubbles of hydrogen which come off during any time, the weight or the volume of this hydrogen is exactly proportional to the number of coulombs of electricity that have passed through the liquid.

The weight, measured in grammes, of any constituent of an electrolyte which is liberated by the passage of one coulomb of electricity, is called its *electro-chemical equivalent.* If we pass one coulomb of electricity through dilute sulphuric acid and it liberates at the — pole ·000010384 grammes of hydrogen; this number is the electro-chemical equivalent of hydrogen. Instead of filling our lantern voltameter with dilute sulphuric acid we may fill it with a solution of a metallic salt, such as acetate of lead (sugar of lead) or nitrate of silver. Putting into the trough a clear strong solution of the former salt, I now project the image of the electrodes upon the screen and pass the current. Immediately we see from the negative electrode beautiful frond-like crystals growing out. These are crystals of metallic lead. From the other pole small bubbles escape, which are oxygen. On reversing the current the crystals gradually wither away, disappear on one pole and appear on the other. If we perform the experiment with nitrate of silver we get a similar effect. If one coulomb of electricity passes through the solutions of these metallic salts, it electrolyses or extracts out from them ·001118 grammes of silver, or ·0010716 grammes of lead respectively, and these numbers are called the electro-chemical equivalents of silver and lead. Frequently, instead of using coulombs as a unit of quantity, practical men use the larger unit of the ampère-hour, which is 3600 coulombs, and the electro-chemical equivalents per coulomb and per ampère-hour are as follows for a few metals:—

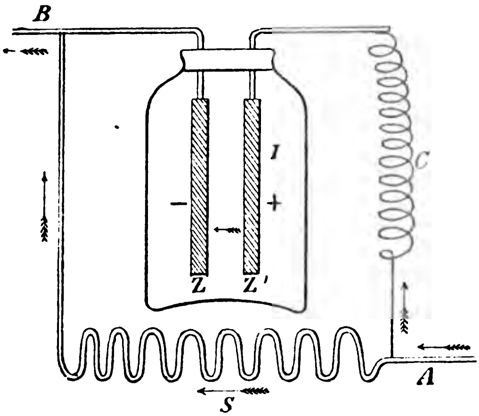
	Electro-chemical Equivalents.	
	per coulomb.	per ampère-hour.
Hydrogen ..	·000010384 grms.	·03738 grms.
Gold	·00067911 „	2·44480 „
Silver	·00111800 „	4·02500 „
Copper	·00032709 „	1·17700 „
Zinc	·00033696 „	1·21330 „
Lead	·00107160 „	3·85780 „
Nickel	·00030425 „	1·09530 „

The electro-chemical equivalents of different metallic elements are proportional to their combining equivalents. We may in a general way explain this phrase, combining equivalent, to be the relative proportions in which the metals combine with chlorine to form chlorides. Thus, one atom of chlorine is capable of combining with one atom of hydrogen, but three atoms of chlorine combine with one of gold, one atom with one of silver, and two atoms with one atom of copper, zinc, lead or nickel, and the relative combining proportions are 1, 65·4, 107·66, 31·5, 32·45, 103·2, 29·3, for the metals in order stated, and these numbers are proportional to the electro-chemical equivalents. Practically it is found that the best electrolytes to use for measuring quantity of electricity are either silver, zinc, or copper salts. With copper we proceed in the following way:—

Take two plates of copper and let them be thoroughly cleaned, best by dipping for a moment or two in strong nitric acid. Place these plates at a fixed distance apart in a vessel containing a strong solution of sulphate of copper, having added to it about 5 per cent. of sulphuric acid. The plates are first carefully dried and weighed before placing in the solution. The current is then passed through the solution from one plate to the other; the negative plate will have a deposit of copper produced upon it. In order to make a firm deposit the size of the plates has to be regulated to the amount of electricity which passes per second. For every

ampère of current or coulomb per second we have to allow at least two square inches of plate surface. If the current density or ampères per unit of surface is greater than this, the deposit of copper will be flocculent and non-adherent. After the current has passed for a certain observed time, the copper plate on which the deposit is formed is removed, washed, dried, and quickly weighed. The gain in weight in grammes due to deposit divided, by ·00032709, gives the number of coulombs of electricity which have passed through the voltameter. For accurate research it is better to use a silver salt. In Edison's system of electric lighting he employs a meter to measure the quantity of electricity distributed to each customer and the meter is a zinc volta-

Fig. 42.



Edison's Electric Meter.

meter. Two zinc plates, about an inch wide and three inches long, are placed in a bottle (see Fig. 42), and fixed at a certain distance apart. The bottle is filled with a solution of zinc sulphate. A portion of the current entering a

house is sent through this cell from plate to plate, the remainder of the current (about 999 thousandths) passing by a German silver shunt, S, and one thousandth passing through the voltameter, I, which contains the zinc plates ZZ′ immersed in a solution of sulphate of zinc. The plates are weighed before placing in the bottle, and then after the passage of a certain current are weighed again; the increase in weight of the plate Z, measured in grammes, and divided by 1·2133, gives the quantity in ampère-hours which has passed through I, and if the shunt ratio or fraction of division of the current is known, then the total quantity passing both through shunt and through the voltameter is also known. In order to preserve this shunt ratio constant at all temperatures, a coil of copper wire, C, is placed in series with the voltameter, the resistance of which is such that the increase of its resistance with rise of temperature just balances the decrease of resistance of the voltameter, due to the same cause. A combination of compensated and shunted voltameter had previously been suggested by Mr. J. T. Sprague as a quantity meter.

The researches of Lord Rayleigh have shown that under certain precautions the silver voltameter affords means of measuring electrical quantity with very great precision. The process consists in decomposing a neutral solution of 15 per cent. strength of pure silver nitrate. The solution is placed in a platinum crucible or basin and a piece of pure silver used as an anode. The crystalline deposit of silver is washed, dried, and weighed. 4·0246 grams of silver are deposited per ampère-hour. The anode should be wrapped round with a piece of filter paper to prevent separated portions from dropping on to the deposit and being reckoned with it.

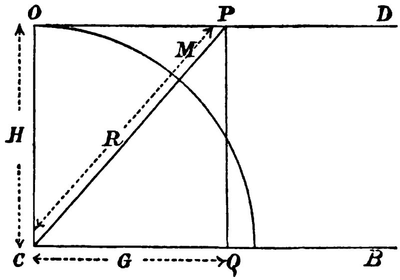
§ 41. If we have to measure a current which is very nearly constant or can be maintained so, then a quantity meter serves also as a current meter or ampère meter. For

the quantity of electricity measured in coulombs which has flowed through the circuit in any time, divided by the number of seconds in that time, obviously gives us the coulombs per second or the ampère strength of that current. This method of measuring currents is called the electrolytic method, but it is not applicable to currents whose strength is variable. We pass now to consider the method of measuring the instantaneous strength of a current. The simplest method is that of the tangent galvanometer. If a conducting wire be bent into a circle whose diameter is very large, compared with the radius of cross section of the wire, then, when a current traverses this circle it creates a magnetic field in the interior space which at the centre of the circle is perpendicular to the plane of the circle. The strength of the field in C.G.S. measure, at the centre of the circle, is equal approximately to $\frac{22}{35}$ multiplied by the ampère current flowing in the circle divided by the radius of the circle in centimetres.

We may put this statement in another way, and say thus: the current measured in ampères flowing in the circular conductor is numerically equal to $\frac{35}{22}$ multiplied by the product of the radius of the circle in centimetres, and the strength of the magnetic field at its centre in C.G.S. measure. Hence, if we can find some simple method of measuring the strength of the magnetic field at the centre of a circular current, we shall have at once, by a simple multiplication, the value of the current producing it. The simplest way to measure a magnetic field is to compare its strength with that of a known field, whose lines of force are at right angles to it. For instance, the strength of the horizontal component of the earth's magnetic field is known at different places on the earth's surface. Let the circular conductor be placed with its plane in the magnetic meridian. Then the lines of force at the centre of the circle, due to the current flowing round it, are perpendicular to the magnetic meridian. Hence, at

the centre of the circle we have two sets of lines of force, at right angles, one due to the earth's magnetism and the other due to the magnetism of the current in the circle. Let the disposition of these lines be denoted by the straight lines H and G (see Fig. 43), in which H represents in direction

Fig. 43.



and magnitude the horizontal field of the earth and G represents the field due to the coil; then the resultant or joint effect of these two magnetic forces is a magnetic force represented by the diagonal, R, of the parallelogram formed on H and G as sides.

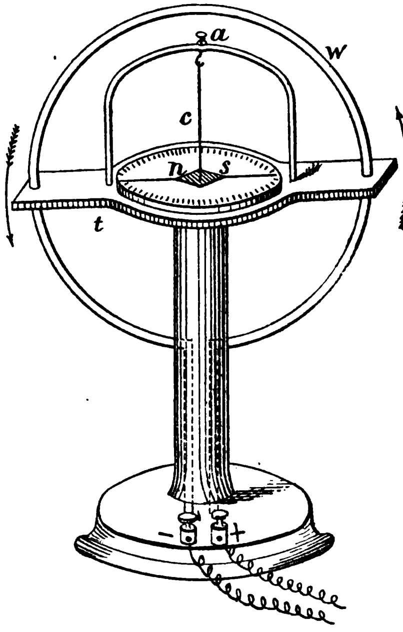
At the centre of the circular conductor, suppose a very small magnetic needle to be suspended. It will take up a certain direction which depends upon the direction of the resultant force, R. The needle, in fact, lies along the direction of the resultant magnetic force. By means of a scale of degrees it is easy to find the angle which the direction of the needle makes with the meridian, that is to say, the angle O C P, included between the direction of H and the direction of R. We have now these two facts: we suppose ourselves to know the value of H, or the earth's magnetic field, and the value of the angle which the resultant force R, due to the joint effect of the magnetic force of the earth and the coil, makes with the direction of H, and it is required to find

the magnitude of G, or the magnetic force of the coil alone. On a sheet of paper take any line C O to represent H, the earth's magnetic force. With centre C and radius C O describe an arc of a circle, and mark off a number of degrees on the arc, starting from O, equal to the angle by which the little magnetic needle at the centre of the coil is deflected from the meridian. Through C and M draw a line C P, cutting a line O D at right angles to C O in a point P. Then on the same scale on which O C represents H, or the earth's magnetic force, O P represents G, or the magnetic force of the current in circle, and we have seen that the value multiplied by $\frac{35}{22}$ and by the radius of the circular coil in centimetres gives the value in ampères of the current flowing in the circular conductor.

Such an arrangement of a circular coil placed with its plane in the magnetic meridian, and a small magnetic needle or compass placed at its centre, is called a tangent galvanometer. Instead of a single circle of wire we can advantageously employ a number of turns of covered wire wound in a rectangular groove turned in the edge of a circular wooden disc, and then instead of ampères we shall have to read in the above rule ampère turns, or the product of the strength of the current, and the number of turns made by the wire. A tangent galvanometer for measuring currents may be made as follows. (See Fig. 44.) A circular disc of wood, eighteen inches in diameter and about one inch thick, has a shallow groove turned in its edge. In this groove is wound with great care two layers of covered wire, which may be No. 16 B.W.G. gauge. The groove must be of such a width that it just takes an exact number of complete turns of wire. The radius of the inmost layer of wire must be measured before putting on the second layer. This is best done by a steel tape, which takes the circumference, and then by dividing this by 6·283 we get the mean radius. The disc has a half-circle cut out of it, and a compass-

needle so placed that the centre of the needle is exactly at the centre of the disc. The needle should not be above an inch long, but may have affixed to it a longer index-needle, which moves over a paper scale. The wooden disc is fixed vertically in the magnetic meridian. The compass-box is

Fig. 44.

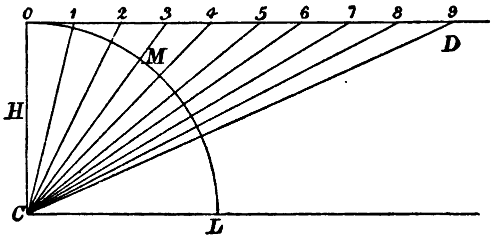


Tangent Galvanometer.

best supported on a shelf which is glued across the opening cut in the disc. Under the needle is placed a card whose circumference should be divided according to the following method, which is called the tangent division of a circle. Let C O (Fig. 45), be the radius of the index-needle, and

therefore of the scale to be engraved, and let O M L be a quadrant of the scale. Through O draw O D perpendicular to O C, and hence a tangent to the circle. Divide O D into equal parts, and through each of these equal divisions, 1, 2, 3, &c., draw lines to C. The points where these straight lines cut the circle O M L, give the tangent

Fig. 45.



Method of dividing a Tangent Scale on an Arc.

divisions of the circle. If in any particular case the needle of the tangent galvanometer is caused to deflect, and set in position C M, as we have seen the magnitude of the current creating this deflection is proportioned to the intercept 04, or portion of the tangent intercepted between O and the point where C M produced cuts O D. Accordingly, by the tangent division of the arc we can at once read off the magnitude of this tangent. Supposing our tangent galvanometer to be complete and provided with tangent scale, we have one more operation to perform before we can deduce at once the value of the current in absolute measure or in ampères. That operation is to standardise the galvanometer or to determine its constant—that is, the value in ampères corresponding to a deflection of one division on the tangent scale. There is a process which enables us by experiment to determine this constant far more simply than by measuring the radius of the coil and the earth's horizontal force.

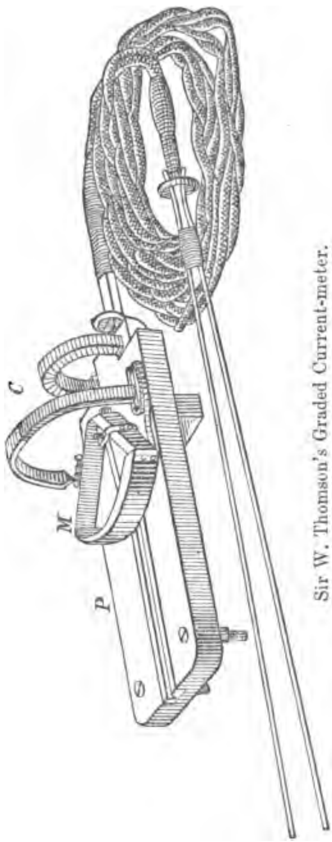
Set up the galvanometer with its circular coil exactly in the plane of the meridian, and adjust the scale so that the needle is accurately at zero. Provide a copper voltameter, and join it up to the terminals of the galvanometer in such a way that a current can be sent in series through the voltameter and galvanometer. Weigh the copper plates of the voltameter; fill it with the solution of sulphate of copper mentioned above, and pass a constant current for a certain time. Observe the deflection of the galvanometer needle during that time. At the end of the period weigh the gain in weight of the negative plate, or better, take the mean of the gain in weight of one plate, and the loss in weight of the other. Divide this weight measured in grams by the time in seconds during which the experiment continued. This gives the deposit of copper per second. Divide this again by number ·000327, and it gives us the ampère current which was passing through the galvanometer.

Call the ampère current A. Then, corresponding to this, we observed a certain deflection of the needle, say D, divisions on the tangent scale. Then A divided by D gives us the ampère current which would produce a deflection of one tangent division. This number is called the constant of the galvanometer. In any other case, if we obtain a certain observed deflection with any current, then the value of the deflection in tangent divisions, multiplied by the constant for the instrument, gives us the value of that current in ampères.

§ 42. A tangent galvanometer is an instrument for measuring the strength of a current by comparing the magnetic field produced by that current at the centre of a circular conductor with the magnetic field due to the earth. Two magnetic fields cannot, however, be very accurately compared if they differ very greatly in strength, and accordingly, if a tangent galvanometer has to be used for measuring large currents it is necessary to make the circular conductor of

great size, in order to obtain a sufficiently feeble field at the centre to compare with that of the earth. To obviate the inconvenience of such very large coils, there are several methods which can be adopted. The first method is the increase of the earth's horizontal field by the addition to it of a stronger field, so as to obtain a known field of comparison of greater strength. This may be done by permanent magnets, as in Sir W. Thomson's graded galvanometers. At one end of a board or supporting table P, is fixed a small circular coil of wire, or it may be of copper tape C. (See Fig. 46.) On the table is placed the magnet-box M, containing a very short magnet and pointer moving over a tangent divided scale. The magnet-box is capable of sliding backwards and forwards so as to place the magnet at any position on the axis of the circular coil, either at the centre of the coil or at some point outside the coil lying on its axis. Over the coil and half embracing it is

Fig. 46.



Sir W. Thomson's Graded Current-meter.

a semicircular permanent steel magnet, whose poles are so placed that its lines of force lie in the plane of the coil. To use the galvanometer it is placed with the table so arranged that the plane of the coil is in the magnetic meridian, and the controlling magnet so placed that the direction of its field is added to the horizontal field of the earth. There is a screw adjustment for making slight changes of position of the magnet. The adjustment of the magnet is known to be correct when the pointer of the small needle points to the zero of the scale, both when the magnet is removed and when it is in its place. When the magnet is in its place the little magnetic needle of the galvanometer is in a powerful magnetic field whose lines of force are in the direction of the plane of the coil. Hence if any current is passed through the coil it tends to deflect the needle, and is opposed in the effort by this fixed magnetic field. The instrument has a large range owing to the power of displacing the magnet-box out of the plane of the coil. In order to use this instrument it is necessary to obtain the value of one degree of the tangent scale, and this is done, generally, either by a copper-deposit method or by another method to be explained later. In any case it is found that the constant of the instrument gets less and less as time goes on. The reason for this is that the permanent steel magnet gradually loses its magnetism, and hence the instrument continually requires fresh determination of its constant. The presence of slight errors in the position of the galvanometer coil, and of the graduation of the tangent scale, make it necessary, for greater accuracy, to obtain values of the constant corresponding to different deflections and different distances of the magnet-box along the table, and to select the proper constant corresponding to any deflection. In order to surmount the difficulties associated inseparably with the employment of *impermanent* steel magnets, Messrs. Crompton and Kapp have devised a current galvanometer which has many points

in its construction of great interest and ingenuity. In it the steel magnet is replaced by an electro-magnet. Diagramatically the arrangement is somewhat as shown in Fig. 47. A B C is supposed to represent a coil of the galvanometer

Fig. 47.

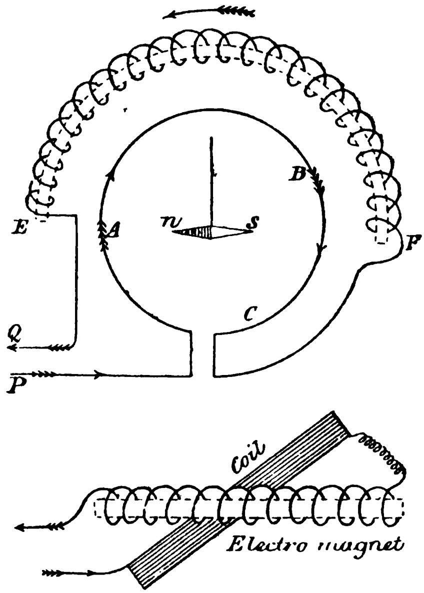


Diagram of Crompton and Kapp's Current-meter.

through which the current flows. N S is the small magnet which is deflected by it. Surrounding the coil is an electro-magnet E F, consisting of a very thin, soft, well-annealed iron wire wound over with covered wire. This electro-magnet is so placed that it forms a magnetic field which is very nearly uniform at the point where the needle N S is situated, and the direction of this field is such as to oppose the magnetic

effect of the current in the coil A B C. The electro-magnet is joined up in series with the coil. When a current is passed through the coil A B C and the electro-magnet coil, the current in the coil tends to deflect the needle out of its plane and make it take up a position at right angles to the coil, whilst the magnetic field of the electro-magnet tends to drag the needle back into the plane of the coil. For very small currents this magnetic restoring force, due to the electro-magnet, would vary with and increase with the current; but as the iron wire in the electro-magnet is very thin it is very soon saturated with magnetism, and hence, for currents greater than a certain limit, the magnetism of the electro-magnet, as far as the iron is concerned, does not go on increasing, but tends to a fixed limit as the iron becomes saturated.

Part of the magnetic effect of the electro-magnet depends upon the current in the wire spiral round it, and this part goes on increasing with the current. By the ingenious device of placing the deflecting coil A B C at a small angle to the electro-magnet, as shown on plan annexed, the magnetic effect of the current in the mere wire winding or coils of the electro-magnet may be neutralised at the centre of the coil, and the electro-magnet winding alone be rendered, so to speak, inoperative in affecting the needle. Above and beyond a certain value of current the iron of the magnet is saturated, and hence provides us with what is required, namely, a constant magnetic field. We are thus relieved from any difficulties which arise, as in the case of steel magnets, from gradual change of strength. The electro-magnet has always the same strength, and there is a perfectly definite deflection of the needle for each value of the current passing through the coils. The only difficulty which arises in connection with such an instrument as this, is the tendency of a long thin iron wire of this kind to retain strongly residual magnetism, and fail to de-magnetise itself, but this effect

would only prevent the return of the indicating needle to zero when the current was stopped, but would not prevent the instrument from giving a definite and fixed deflection, corresponding to a definite and fixed current passing through the coils.

§ 43. In order to obtain a tangent galvanometer, which should be capable of measuring large currents and yet not be too unwieldly, Prof. C. F. Brackett has designed a form on which there are two concentric coils. The current to be measured goes round these coils in opposite directions. Their magnetic effects are, therefore, opposed at the centre. It is possible then to pass large currents through the double coil and yet obtain deflections of the needle, which do not exceed 45° or 50°.

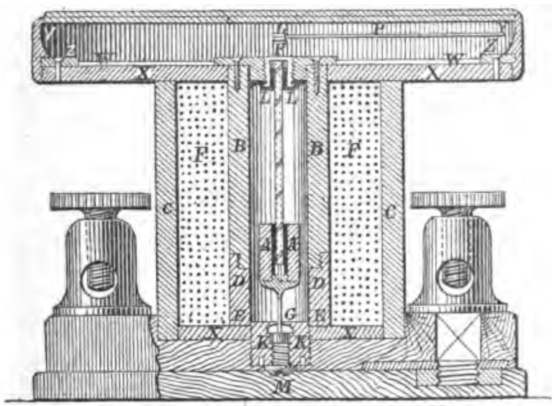
In designing tangent galvanometers which are intended to be standard instruments, care should be taken so to dispose the wires which convey the current to and from the galvanometer that they do not affect the needle. The best way to do this is to make one conductor a tube of brass or copper, and the other a rod concentric with it, but insulated from it by a covering of rubber. Such tubular lead is made long enough to prevent that portion of the lead and return which is nearest the galvanometer from affecting the needle.

In using a tangent galvanometer, it is not advisable to compare currents which cause very great deflection of the needle, say to 70° or 80°, because at these degrees the tangents begin to increase very rapidly for small angular increase, and hence a very small error in the angular reading causes a very great one in the corresponding tangent.

§ 44. There is a class of instruments which depend upon a principle first clearly stated by Faraday, viz. that a small piece of iron if placed in a magnetic field of unequal strength tends to move from weak to strong places in the field. Of this type are the newer instruments of Profs. Ayrton and Perry. The special feature of these instruments is the

dispensing with a permanent magnet, and the employment of a new form of spiral spring, of such a nature that, when it is fixed at one end and stretched this stretching is accompanied by a rotation of the free end. In an ordinary spiral spring there is no such rotation. The form of the ammeter is shown in Fig. 48.

Fig. 48.



Ayrton and Perry's Spring Ammeter.

B B is a thin tube of charcoal iron, attached to its lower end to a tube D D of brass. Over this tube is wound wire, and outside this an iron shielding tube C C. In the inner tube hangs a small mass of soft iron A A, suspended by the spiral spring. This spiral spring is fixed at its upper end. The short cylinder of iron A A hangs at such a depth in the inner tube that it just projects from the inner iron tube. When a current passes through the coils, a strong field is formed below the iron piece, and it is dragged down. Attached to the iron piece is a spindle which runs up through the spring and carries at its upper end a hand or pointer.

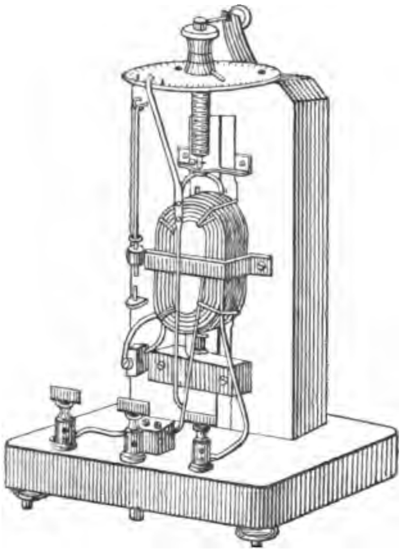
When the spring is stretched the iron mass rotates at the same time that it is pulled down, and indicates this rotation by the hand upon the dial. The amount of rotation depends upon the amount of longitudinal extension of the spring, and this in turn depends upon the strength of the current in the coils. The external iron tube and top and bottom iron plates afford an effectual screening from external magnetic influences, so that the magnetic field just below the movable piece of soft iron depends on the current in the coils and on nothing else. This instrument has a large range of deflection over which it can be used, and as the increase of deflection is in simple proportion to the increase of the current, the higher divisions of the scale are not crowded together as in the case of tangent division of a scale for tangent galvanometers. The instruments as now made are graduated to read directly in ampères. We shall allude in considering voltmeters to other instruments of a smilar character.

§ 45. None of the instruments described above are adapted for measuring alternate currents—that is to say, currents of electricity which are not constant in direction, but made up of alternate short fluxes, or impulses of electricity in opposite directions. In measuring such currents we employ instruments called dynamometers, of which the best known is Siemens'. (See Fig. 49.)

If a movable coil of wire is suspended in the interior of a fixed coil, the suspension being managed either by hanging the coil by its leading-in wires, or by a suspending spring, and dipping the ends of the coil into mercury cups, then we can send one and the same current through both coils. Let the coils be fixed initially, so that their planes are at right angles to one another. If a current passes through both coils it will tend to pull the coils round into the same plane, and the force with which it does this is proportional to the square of the strength of the current. Let the movable coil be hung by a spring or stiff wire, so that this

tendency of the current to pull the coils into one plane is resisted; then, since the angle of torsion is proportional to the force, it follows that the current strength varies as the square root of the angle of torsion. Let us suppose that

Fig. 49.



Siemens' Dynamometer for Measuring Alternate Currents.

in measuring two different currents we obtained deflections of the movable coil, amounting in one case to 25°, and in the other case to 49°. Then the currents are in the proportion of 5 to 7, or of square root of 25 to square root of 49.

In the usual form of Siemens' dynamometer the coils are rectangular in shape. The fixed coil is fastened to a vertical support; the movable coil is hung by a spiral spring, which depends from the centre of an index-

needle, which moves over a circular scale of degrees. The needle moves round its axis stiffly. From the bottom of the movable coil hang down two wires, which are the ends of the coil. These wires dip into mercury cups. By this means currents can be led into the movable coil without much interfering with the freedom of movement. The connections are so made that the current to be measured goes through both coils in series. To use the instrument, it is set up with the plane of its movable coil at right angles to the meridian. The two coils are so adjusted that they are exactly at right angles to one another. On passing the current through the coils the electro-magnetic force twists round the movable coil against the torsion of the spring. By turning the index-needle round, and with it the upper end of the spring, a force of torsion can be applied to this coil sufficient to bring it back into its initial position at right angles to the fixed coil. The needle on the dial then reads off at once the number of degrees of torsion which measures the electro-magnetic force between the coils. The current strength is proportional to the square root of the angle of torsion. Accompanying each instrument is a table which is calculated out, so as to show at one glance the current corresponding to each division on the scale.

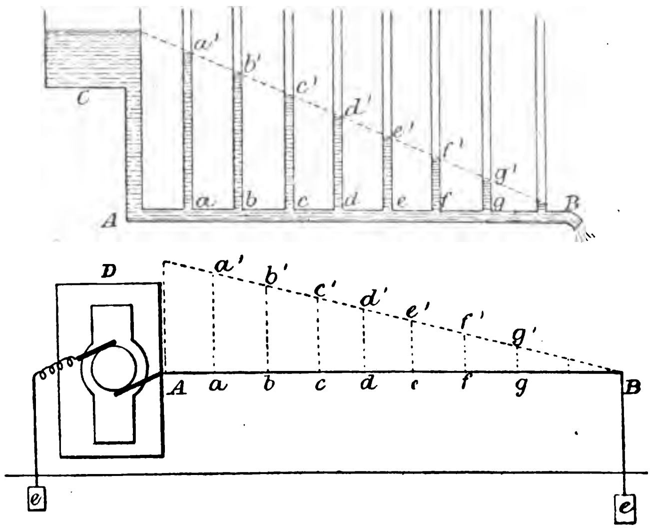
When a dynamometer is employed to measure alternate currents, the indications it gives are proportional to the mean of the square of the current at every instant during its complete period or phase. The square root of the mean square of the current strength is not, however, the same thing as the true mean current. In the case of alternate currents, where the use and fall of current strength follows what is called a harmonic law, the actual mean current is 10 per cent. less than the square root of the mean of the squares of the current at each instant during the period.

LECTURE VII.

§ 46. In addition to the instruments for the measurement of quantity and current, we have next to consider those devised for the measurement of electromotive force. Let us return for one moment to our hydraulic analogy. Let A B (Fig. 50), be a long horizontal pipe, which is in connection at one end with an elevated cistern of water. Water flows down from the cistern and flows along the pipe. The force driving the water along the pipe is the weight of the water in the cistern. The depth of the water at any point below the free surface of the water in the cistern is called the "head" of water at that point. Suppose at various points along the horizontal pipe a series of vertical tubes inserted, the water will rise in these to a height proportional to the pressure at the point where they are inserted. Accordingly we should find that the height of water in each of these pressure-tubes diminishes from tube to tube as we proceed towards the outlet. Considering any pressure-tube *a*, the height *a a'* measures the hydrostatic pressure at *a*, and the height *b b'* that at *b*. The force urging the water from *a* to *b* along the pipe is the difference of pressures at *a* and *b*. This might be called the water-motive force between *a* and *b*. The gradual fall of pressure along the pipe from *a* to *g* is called the hydraulic gradient. Between any two points in the pipe there is a flow of water measured in so many gallons or cubic inches per second, which flow depends upon the difference of pressure at those points, and the resistance of the pipe. These facts in hydraulics, or in water-flow, have their exact parallel in the case of electric-flow. Let D (Fig. 50) be a dynamo machine, and let A B

be a long lead, with its farther end to earth. Let the other brush or terminal of the dynamo be also connected to earth. The dynamo when in action is just like a cistern of water at a high level, or a pump; it urges electricity into the lead

Fig. 50.



A B, and at every point *a b c* in the lead there is a certain electric pressure analogous to the water-pressure in the pipe. The electricity flows in the lead between any two points *a* and *b*, in virtue of a *difference* of electrical pressure between these points; and the flow or quantity per second, or current strength, is determined by two things; this difference of pressure and the resistance of the piece of lead between the points considered. Along the lead there is a regular fall or gradient of pressure represented by the sloping lines a' b' c'.

As we have seen in the previous lecture, the difference of pressure or electromotive force between any two points is

connected with the flow or current by a simple law. For a conductor of given resistance, the difference of pressure between its ends is proportional to the electric flow or current in it. Hence any instrument of constant resistance, which can measure electric current, can be used to measure difference of electric pressure. But there is one important qualification of the above remark to be made. Imagine that there are two cisterns of water at different levels, we might, with certain precautions, determine what that difference of level was, by uniting the cisterns by a pipe and ascertaining the flow of water which the difference of pressure produces. If, however, we were to employ as a testing-pipe a wide pipe permitting the flow of a great quantity of water through it, the very act of attempting to measure the difference of level would alter it. To employ the method successfully we should have to use a very narrow or fine pipe, not permitting any very great flow, and hence not disturbing much the difference of level required to be measured during the time of the experiments. Exactly in an analogous manner can we measure the difference of electrical pressure between two points. We provide a galvanometer or current measuring instrument of high resistance, that is to say, one not permitting much electrical flow through it. This is inserted between the points whose difference of electrical pressure is required. Its actual readings are proportional to the current going through it, and that is proportional to the difference of pressure between these points.

§ 47. Instruments for the measurement of difference of pressure, or potential and electromotive force, are called variously voltmeters or potential galvanometers.

The instruments we have already described, as devised by Sir W. Thomson, Messrs. Crompton and Kapp, and Professors Ayrton and Perry, for the measurement of current strength, are altered into voltmeters by the simple exchange of a coil of very high resistance for one of low. Whereas in

the ammeter the resistance of the coil will be perhaps one-tenth of an ohm, or even less; it requires, when intended for use as a voltmeter, to have a long, fine wire coil of 1000 to 5000 ohms resistance.

With regard to errors introduced by variability of the controlling field, due to change of magnetism of permanent magnets if used, voltmeters are liable to the same kind of errors as ampère-meters. Also, if springs are used, change of temperature will affect their elasticity. In addition, however, voltmeters are liable to an error due to the heating of the coils by the current traversing them. In an ampère-meter the resistance of the coils is generally so very small a fraction of the total resistance of the circuit, that the small change due to rise of temperature of the coil will not at all perceptibly alter the value of the current strength. With voltmeters it is quite otherwise. In their case the reading of the voltmeter is actually a reading of the value of the current traversing it, and assuming it to be applied to two points of perfectly constant difference of potential, the current, and, therefore, the reading, will vary inversely as the resistance of the coil. Hence the current, by heating the high-resistance coil, increases its resistance, and makes the voltmeter read lower than it should do by an amount proportional to the change in resistance of the wire. The co-efficients of thermal variation of resistance, or the amount by which one ohm resistance becomes increased when the conductor is heated 1° centigrade, are given below for several metals:—

Material.	Thermal variation of resistance per degree centigrade.
Platinoid	·00021
Platinum-silver	·00031
Gold-silver	·00065
German-silver	·00044
Cast-iron	·00080
Copper	·00388

A wire of German-silver whose resistance at the freezing point is one ohm, becomes, at 1° centigrade, 1·00044 ohms, and at 2° C. 1·00088 ohms, and so on.

A coil of copper, whose resistance at 0° C. is 1 ohm, becomes, when heated to 10° C., 1·0388 ohms, or experiences a rise in resistance of nearly 4 per cent.

Nearly all pure metals, except mercury, have a variation of something of a like order; but alloys, and particularly the alloy of German silver and tungsten, called *platinoid*, has not one-tenth of the variation co-efficient of copper.*

Accordingly, in using a voltmeter, it should never have the current passed through it for more than the instant of reading, since if its coils are of copper wire it may easily happen that a prolonged passage of the current through its coils will so increase the temperature as to make its readings (even if originally correct) 5 or 10 per cent. in error by defect.

The desirability of obtaining a voltmeter which should be free from springs, permanent magnets, or electro-magnets, caused Sir W. Thomson to devise the following arrangement as a working voltmeter within certain range. A long, light arm of aluminium P is balanced like a steelyard on knife-edges of phosphor-bronze resting on glass plates (Fig. 51). At one end of this arm is suspended a very small cylinder I of soft iron, and below this a balance weight of copper. The iron cylinder hangs in the interior of a small coil of fine wire C, having a resistance of about 200 ohms, and wound more thickly with turns of wire at the top than at the bottom. The iron weight hangs near the bottom open end of this coil. When a current is passed through this coil it produces in its interior a magnetic field, which is stronger near the top than at the bottom of the interior of the coil. The little cylinder of iron is accordingly moved up from weak to strong places in the field in opposition to gravity, and for every given

* This material drawn into wire can be procured from the London Electric Wire Company, Golden Lane, London.

current in the coil there is, within certain limits, a corresponding place of equilibrium for the iron, and therefore position for the steelyard arm. The steelyard arm moves over a scale which is directly marked in volts, and when the terminals of the instrument are attached to any conductor,

Fig. 51.

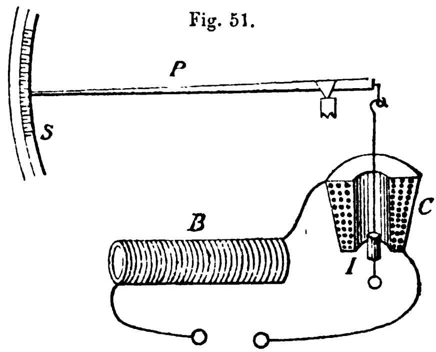


Diagram of Sir W. Thomson's Gravity Voltmeter.

between which a difference of potential is maintained, the instrument gives at once the value in volts. In order to give the instrument a sufficiently high resistance, there is a coil of platinoid wire B attached in series with the working coil, and which has a resistance of some 2000 ohms. There is also attached a current reverser, by means of which the current in the coil can be rapidly reversed, and any traces of remanent magnetism got rid of from the iron. In this apparatus the force with which a small piece of iron tends to move from weak to strong places in a magnetic field is weighed against the constant force of gravity.

A short, stumpy piece of soft iron, if placed in a magnetic field, takes a magnetic state depending on that field, and if removed it loses immediately its magnetism. A long, thin bar does not. Hence, if placed in fields of different strength

successively, its state is dependent on its previous magnetic history. A short, squat piece of soft iron has, so to speak, no magnetic memory. Its past magnetic history is immediately obliterated when placed in a new magnetic field.

§ 48. The above voltmeters depend upon electro-magnetic action for their operations, and none of them are suitable for measuring electromotive force of alternate currents, or rapidly reversed electromotive force. One of the best and most useful instruments for measuring electromotive force of alternate currents not exceeding about 200 or 300 volts, is that of Captain Cardew. It depends on the elongation which a platinum or platinoid wire experiences when a current is sent through it. In its simplest form it consists of a long tube, part of brass, part of iron, to the top of which a fine wire of platinum silver is affixed. The lower end of the wire is kept tight by a spring, and acts through the agency of a multiplying motion upon an index hand which traverses a dial, and which shows the smallest elongation of the wire. This wire, together with a resistance coil in series if required, is connected to the two points between which it is desired to measure the difference of potential. A current traverses the wire proportional to the electromotive force, and it is heated. After a very short interval of time it takes a steady temperature, which is reached when there is a balance between the rate at which heat is generated in the wire, and the rate at which it is emitted or lost by radiation, air convection and conduction from the ends. The permanent elongation of this wire is a measure of the rate of generation of heat in, and therefore of the average electromotive force at the ends of the wire.

It is obvious that the material of which the containing tube is made should have the same co-efficient of expansion for heat as that of which the wire is made. If a platinum-silver wire is used, the tube should be made two-thirds of brass and one-third of iron.

The great value of Cardew's instrument is, that it gives us a reliable means for the measurement of the electromotive force of alternate currents. In an alternate current dynamo, the current is not continuous, but is reversed in direction several hundred times in a minute. Accordingly, the direction of the electromotive force between the terminals is reversed as frequently. The heat generated per second, and therefore the elongation of a wire traversed by an alternate current, is independent of the direction of the current, but depends only upon the mean of the square of the current strength. Also, such a straight wire and coil can be constructed so as to have a very small self-induction, and hence its *impedence* will, within certain limits, be approximately constant, and independent of the rapidity of the reversals of the current.

§ 49. We proceed next to discuss a mode of measuring electromotive force and current by means of an instrument called a *Potentiometer.* If a very uniform wire of high resistance, stretched on a board, has its ends attached to the poles of a cell or two of a secondary battery, there will be produced in this wire a regular gradient of electric pressure, and the fall in potential along this wire between any two points on it will be proportional to the resistance, and in this case to the length of the wire between the chosen points. Let wires leading from the terminals of a very delicate high resistance galvanometer be applied to any two points on the wire. The galvanometer will give a deflection proportional to the fall in potential or step of pressure between the points at which these terminals are applied. If we insert in the galvanometer circuit a galvanic cell of a kind to be described presently, and called a standard cell, in such a direction as to oppose the current produced by touching two leading wires to two points on the fine wire (called the potentiometer wire), then it will be possible, by sliding one of the contacts along, to find such a length of the fine

wire, that the fall in potential along it is just equal and opposite to the electromotive force of the standard cell. When this is the case, we have, by a simple calculation, the fall in volts per inch, along the potentiometer wire. If

Fig. 52.

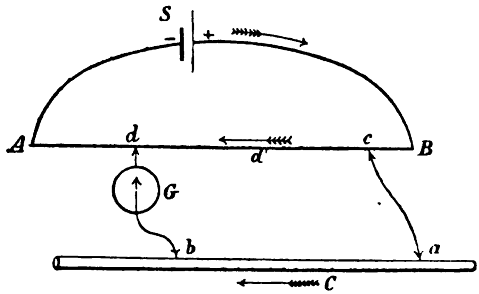


Diagram of Potentiometer.

now we desire to determine the difference of potentials between any two points, all that has to be done is to connect these points by wires with the potentiometer wire, and slide one or both contacts along the potentiometer wire until a delicate galvanometer, inserted in the circuit of one of these "feeling" wires shows no current. Let A B (Fig. 52) be the fine potentiometer wire, and let its ends be kept at a certain difference of potential by a few cells of secondary battery S. Suppose, by means of a standard cell, we have determined the fall in pressure per inch along this wire, and we desire to determine the difference of potential or fall in pressure between two points *a b* on another conductor C traversed by a current. Take fine wires and connect the points *a b* with two points *c d* on the potentiometer wire, and move the points of contact *c d* until there is no electric current detectable in *a c* or *b d*. Then the difference of potential between *a b* must be equal to that between *c d*, and this is known from the experiment with the standard cell.

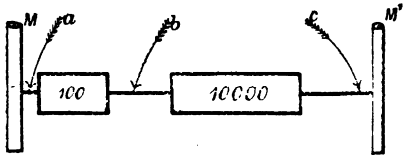
The diagram on Fig. 52 shows the proper mode of making the connections in order to determine the difference of potentials or pressure of two points situated on a conductor. A B is the stretched wire of the potentiometer, preferably a wire of platinoid about 40 ohms resistance and 4 metres long. S is a secondary cell which keeps the ends of the wire A B at a fixed difference of potential equal to about 2 volts. Hence if A B is a uniform wire there is a regular gradient of pressure down it. Let C be a conductor through which is flowing a current. Let any point *a* on C be joined by a fine wire with B, and let any other point *b* on C be joined through a high resistance reflecting galvanometer with some other point *d* on A B. By sliding the contact *d* along A B it will be possible to find a place where the galvanometer shows no current, provided the difference of pressure between *a* and *b* does not exceed 2 volts. By performing the same experiment with a standard cell, to be described presently, it is possible to find a position *d'* for which there is no current through the galvanometer when the contact wires *a b* are touching the poles of the standard cell. When this is the case, we have two lengths, *c d* and *c d'*, which are proportional respectively to the difference of pressures between *a b* on the conductor and that between the poles of a known standard cell. A simple proportion then gives the value of the difference of pressure between *a* and *b*.

A potentiometer arrangement gives us the means of measuring either electromotive force or current strength. Let M M' (Fig. 53) be two mains between which there is an electromotive force of something like 100 volts which it is required to measure. Provide two resistances of about 100 ohms and 10,000 ohms. It is not necessary that the actual value of these resistances should be very accurately known, but it is necessary that the ratio of their magnitude should be determined. Let them be inserted in series between the mains.

The total resistance will be then 10,100 ohms, and the electromotive force of 100 volts will send a current of about 1–101th part of an ampère through them.

Now the step, or increase of pressure in passing from *a* to *b* across the 100 ohms is just 1–100th part of the step or

Fig. 53.



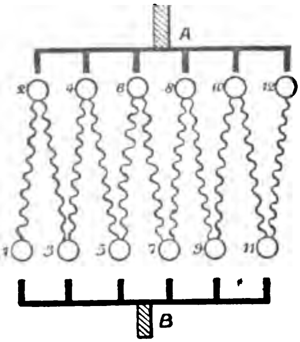
increase of pressure in passing from *b* to *c* across the 10,000 ohms; accordingly, if we measure the difference of potential between *a* and *b*, then that between *a* and *c* will be 101 times as great. We measure the former by the potentiometer as it will be something near one volt, and then multiplication by 101 gives us the difference of potential between M and M′. Any small variation of temperature does not affect the result, provided that it affects both of the resistances proportionately, and this will be the case if they are made of the same material and arranged in the same way.

Turning to the diagram, Fig. 52, we now see that in order to measure the current flowing in the conductor C, all we have to do in addition to measuring the difference of pressure between *a* and *b*, is to measure the resistance between *a* and *b*. Suppose *a* and *b* are the ends of a low resistance whose value is known, the value of the current is given at once by dividing the value of the difference of potentials in volts between *a* and *b*, by the resistance between *a* and *b* in ohms.

The best way to construct a low resistance whose value can be accurately ascertained is to proceed as follows: Take eleven wires of German silver, each having a resistance

of $\frac{1}{10}$th of an ohm and being about two yards long. These wires are to be joined up in a zig-zag fashion between two rows of mercury cups. (See Fig. 54.) The united resistance in series of these eleven wires between the mercury cups 1 and 12 is of course $1\frac{1}{10}$th of an ohm. Let there be provided two combs of thick copper wire, A and B, which can drop simultaneously into the mercury cups on each scale, so as to join up cups 2, 4, 6, &c., and 1, 3, 5, &c. If the combs are inserted, then the eleven wires are joined up in parallel, the united resistance between A and B is $\frac{1}{110}$th of an ohm. It is easy to construct a small resistance of known value by joining in parallel resistances of large value which have been accurately measured. Moreover, any change in resistance of the wires due to heating when arranged in parallel, can be inferred from the change or resistance which can be found when the wires are thrown into series, since the resistance in parallel is $\frac{1}{121}$st of that which it is in series. To use this appliance for measuring a current, say of 100 ampères, we put it in parallel and pass the current through from comb A to comb B. We measure with the potentiometer as above the difference of pressure between A and B. We already know the resistance, hence the current is at once calculated. If we suspect that the resistance has changed, owing to heating by the current we desire to measure, we remove the combs and instantly measure the resistance of the eleven wires in series, $\frac{1}{121}$st part of this is the resistance in parallel, which must be considered in the calculation. It is easy by this means, given a reliable

Fig. 54.

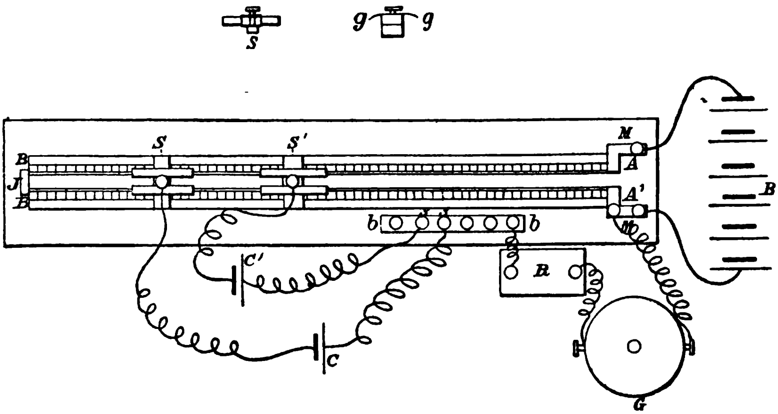


standard cell, to measure very large currents with considerable accuracy and expedition.

As this form of potentiometer is one of great use in the testing-room and workshop, we give here details of its construction and a sketch.

On a stout mahogany board (see Fig. 55) are fastened

Fig. 55.



Potentiometer for comparing Electromotive Forces.

down two boxwood scales, each 5 feet long, divided into inches and tenths; these scales are fixed about $\frac{1}{4}$ inch apart and parallel, so as to form a groove between them. On these scales are stretched two fine uniform German silver wires A B, A′ B′, about ·013 inch in diameter, and having a resistance of about 1 ohm to the foot-run: one end of both wires is soldered to a thick copper junction-piece J, and the other ends respectively to copper pieces connected to terminals M, M′. The wire thus forms one length of about 10 feet stretched over two scales. This forms the potentiometer wire; its length is divided by the scale into

1200 parts, and each tenth of an inch can be divided by the eye into 10, making a possible division of 12,000. To the terminals M, M′ are connected five or six large-gravity Daniell cells, or a few secondary cells.

A very constant E.M.F. can be obtained by using three small accumulator cells, with leads to the terminals M, M′.

To calculate what number of cells are required to maintain a given difference of potential, say 2 volts, at the extremities of the potentiometer wire. Let n be the number of cells, e the E.M.F. of each, and r the internal resistance, and let R be the resistance of the potentiometer wire, and v the required difference of potential at the terminals M, M′; then

$$v = \frac{n e \mathrm{R}}{n r + \mathrm{R}},$$

which determines n. If r is not known, it can be determined by a second experiment, in which v is observed in the case of a given number of cells.

The current along this German silver wire makes a fall in potential at about the rate of 1 volt in five feet. On one side of the board is fastened a broad copper strip $b\,b$, having six terminals fastened upon it. Between the last of these terminals and the end of the scale-wire A′ is inserted a reflecting galvanometer of 5000 ohms resistance, and an additional resistance of 50,000 ohms R. Suppose we desire to compare the electromotive forces of two galvanic cells c and c'.

To the terminals $s\,s$ on the copper strip are connected one pole (like to the pole of the battery B connected to M′) of each of the cells $c\,c'$ to be compared; and the other poles of these cells are connected with sliders S S′ travelling over the wires. These sliders are blocks of wood sliding in the groove between the scales, and overhanging the wires. On them are German silver spring strips as

shown in the figure, and which, when pressed down, make contact with the wire. The strips are backed with leather to avoid the production of thermo-electric currents. By using two of these sliders, we find for each cell the position on the potentiometer wire at which contact has to be made as shown in the figure in order that the galvanometer may indicate no current. The introduction of the resistance R prevents any but the very smallest currents passing in the cells whilst the place of balance is being found on the potentiometer. The German silver strips $g\,g$ on the sliders make contact only when pressed down; so that in the normal condition the cells $c\,c'$ are insulated. With the galvanometer in a sensitive condition it is very easy to read a difference of $\frac{1}{10000}$ of a volt on the wire, and $\frac{1}{1000}$ can be read with great accuracy.

The electromotive forces are read off directly as lengths, since the E.M.F. of each cell $c\,c'$ is directly as the distance of the contact points of their respective sliders from the end A′ of the wire. Great care has to be taken in the first instance to stretch the wire uniformly, and to calibrate it if it presents any want of uniformity of resistance.

§ 50. The third important element in the list of electrical quantities is *Resistance.* Our first consideration is the question of standards of resistance. The British Association Committee charged with the work of reproducing a physical standard of resistance, of which the absolute value had been fixed at 1000 million of centimetres per second,* completed their work by constructing a number of

* Students are sometimes puzzled by the statement that an electrical resistance is measured by a *velocity.* This arises perhaps from assuming that electrical resistance is of like nature to mechanical resistance or friction, and should therefore be measured in some similar manner. Electrical resistance is a name for a certain ratio, viz. the ratio of electromotive force to electric flow for a given circuit of given size, shape, and condition. This ratio can be determined by

coils of wire embedded in paraffin and contained in brass cases. These resistances the committee construed to be, in their opinion, as nearly as possible resistances of 1000 million centimetres per second, and called this unit one *Ohm.* It is now known that this estimate of the value of these coils was in error. But since they have been extensively used and copied, it is better to speak of a resistance equal to that of the mean of all these coils as the *mean British Association unit*, or the mean B.A.U. A very large number of determinations have been made by the most skilled physicists of the relation between the British Association unit and the true ohm. All agree that the B.A.U. is too small. The mean of nineteen different determinations by sixteen different observers make the British Association unit equal to ·9886 of the true ohm. Very great weight ought, however, to be given to Lord Rayleigh's latest determination, which is 1· B.A.U. = ·9868 ohm, as representing the very highest degree of labour and accuracy. In order that there might be agreement on the subject of the unit of resistance, the Paris Congress of Electricians in 1884 defined another unit of resistance. It is the resistance of a column of pure mercury at 0° C., 1 square millimetre in section and 106 centimetres long. This resistance is called a legal ohm, and

$$1 \text{ Legal ohm} = 1{\cdot}0112 \text{ British Assoc. unit.}$$

Hence to transform resistances expressed in B.A. units to Legal ohms, the numerical values have to be reduced by about one and one-tenth per cent.

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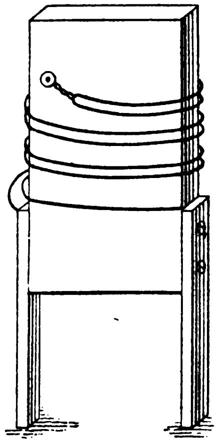
making the circuit move suitably through a unit magnetic field, and then determining the speed necessary to produce in it a unit current. Hence resistance is determinable in terms of a speed, and is said to be of the *dimensions* of a velocity.

In constructing a standard coil intended only as a standard, and not to be subjected to any but very small currents, the material commonly used is platinum-silver wire, double-covered with white silk. The covered wire is baked in an air oven and boiled in paraffin. The most general form of a resistance-coil is a bobbin, to which is attached thick copper legs; the ends of the wire are first soldered to these and the loop of wire wrapped round the bobbin. Makers generally dip these bobbins in paraffin wax, and enclose them in a brass case. In using these coils, only weak currents should be sent through them, as the act of passing even a slight current through the wire heats it, and if this heat accumulates in the wire, it raises its temperature and increases its resistance. It is possible to expose the wire to the air, and to make it in the following way:—To the sides of a rectangular piece of dry mahogany (see Fig. 56) are screwed thick flat copper bars. The wood may be six inches long, two wide, and half-inch thick. The upper and lower ends of these copper rods are tinned. A length of platinum-silver wire is then selected very nearly equal to the resistance it is desired to make.* In selecting the gauge of wire, regard must be taken of the magnitude of the resistance it is desired to make. Speaking generally, it is desirable to have as thick a wire as can be permitted by bulk or

Fig. 56.



Resistance Coil.

* On account of its less variation of resistance with temperature and less cost, platinoid, which is an alloy of German silver with tungsten, is a very good material to use. It is found that the specific resistance of different samples of German silver varies greatly.

cost, but in actual practice the following may serve as a guide:—

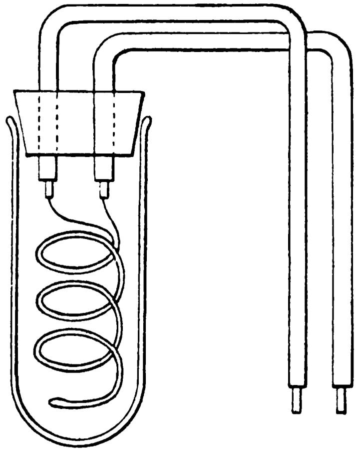
To make a Resistance coil of	Take platinum-silver wire of about	
	Length.	Gauge in B.W.G.
1 ohm	9 feet	No. 22 = ·036 dia.
10 "	42½ "	No. 24 = ·025 "
100 "	133 "	No. 30 = ·014 "
1000 "	675 "	No. 34 = ·010 "

Having cut these lengths of covered wire, they are doubled upon themselves and the ends soldered (using rosin, not acid) to the ends of the copper rods. The wire doubled upon itself is then folded round the wood and the end tied with a piece of silk to restrain it from springing back. If the coils when measured are found to exceed the value required, a little adjustment of the wire has to be made. This is done most easily by stripping the silk off the loop of wire just at the bend for an inch or two, and twisting the well-cleaned wire up into a loop, so as to short-circuit part of the loop of wire. When after measurement, and if necessary, of repetition, the total resistance is nearly what is required, the twisted end is just touched with soft solder to seal it together. It is not so important in making a resistance coil to aim at getting an exact integer value, as to know precisely the true value at some known temperature.

In using such a standard coil in the way to be described presently, the copper legs are placed in mercury cups or soldered to wires. The wire being left open to the air takes its temperature, and that of the wire can be inferred from the temperature of the air with greater accuracy than when the coil is embedded thickly in paraffin. If it be required to determine the resistance of such a coil at zero, it may be placed in a glass jar filled with paraffin oil, which is itself surrounded with melting ice or snow. A useful form of coil may be prepared as follows:—Take a very large glass test-tube (Fig. 57), an inch and a half in diameter, and six inches long. Fit it with an indiarubber cork, through

which pass, water-tight, a couple of very stout copper wires, covered with guttapercha. The copper wires just project inside the cork, and to the ends of these are soldered the ends of the platinum-silver coil. The coil is twisted up inside the test-tube. The guttapercha is stripped off the last inch of the other ends of the copper rods so as to permit them to be dropped in mercury cups. If desired, a third hole can be made in the cork through which a thermometer may be passed.

Fig. 57.



Standard Resistance Coil.

The most accurate way to make a coil of very low resistance, is to combine in parallel wires of high resistance. Thus for example, to make a hundredth of an ohm, take one hundred wires of German silver ·02 inch diameter, and of such length as to measure one ohm each, solder the ends to stout copper pieces so as to make a short cable of one hundred strands. The resistance of this will be $\frac{1}{100}$th of an ohm.

In constructing resistances which are intended to be used with large currents, we have to be guided in our choice of sizes of wires by the additional consideration of the limiting current which can safely be used without over-heating the wire. When a current is passed through a bare wire, the heat generated per second in the wire has to be got rid of by radiation and by contact of the cold air with the surface. If currents of electricity are passed through straight bare wires

of different diameters, until these wires have attained the same steady temperature, at which the heat generation is balanced by the heat loss, it will be found that these currents are nearly in the ratio of the diameters for the same material, but wires of the same diameter but different materials have very different current-carrying capacity. It is necessary to know what currents passed through bare wires, straight or openly coiled, will bring them ultimately to some one steady temperature, say of 60° C. In order to afford data for constructing resistances, experiments were made by passing various currents through coiled spirals of naked wires of different sizes and materials.

A large number of wires were prepared of copper, brass, iron, German silver, each 25 feet long, and of six sizes respectively, Nos. 10, 12, 14, 16, 18, 20 B.W.G., the diameters being given below. These wires were coiled into spirals round wooden rods about one inch diameter, and the turns of the wire well separated, so that each coil or spiral was about 18 inches long. Measured steady currents were sent through these for some hours, and so adjusted that after the temperature had become steady the wires were all at a temperature just about bearable by the hand, that is near 60° C. The currents respectively carried were as follows:—

Size of wire	No. 10 B.W.G.	12	14	16	18	20
	·134 inch diam.	·109	·083	·065	·049	·035
	Currents carried in Ampères.					
German Silver ..	18·75	13·5	8·25	6	4·12	3
Brass	30	18·75	15	9·75	7·5	5·25
Iron	18	11·25	10·5	8·25	5·25	3·75
Copper	49·5	38	26·25	20·25	15	9

These currents passed through the above-described naked spirals bring the respective wires to about a temperature of 60° C., when equilibrium is established; and for the purposes

of measuring currents not more than one-third of the above, currents should be used with wires of the size appended. Thus for 300 ampères, about 50 No. 10 B.W.G. wires will carry it without much sensible elevation of temperature; and by arranging 50 wires so that their resistance can be quickly measured in series, a resistance can be made suitable for measuring the potential at the ends of a known resistance.

In the construction of resistances for use in testing dynamo machines, it is necessary to adopt some form which is cheap, not too bulky, and affords a large surface for radiation of heat. Thin hoop-iron bent into zig-zag shape answers fairly well. Narrow bands of iron wire gauze make an effective resistance for the purpose, as it affords an immense surface of cooling, and can therefore be made to take a very high current density.

One yard of hoop-iron about half-an-inch wide and one thirty-second of an inch thick measures about one hundredth of an ohm. Hence, 100 yards of it make an ohm. Rods of electric light carbon are sometimes employed as resistances, but they are not suitable for use in cases where resistance has to be very definite. One difficulty which attends the use of carbon is in getting effective contacts. The best plan to adopt is to dip the ends in molten paraffin, and after they are well saturated, let the wax harden, then file the surface to free it from wax, and electrotype the ends with copper, and then tin them by dipping in melted solder. To these tinned ends wire connections can then be soldered.

§ 51. We have next to consider the practical measurement of resistance.

One of the simplest and most direct methods which is specially applicable to low resistances, such as the armatures of dynamo machines, is by the method called "comparison of fall of potential." Let it be desired to measure the resistance of an armature of the Gramme or Siemens type. Construct a resistance of one hundredth of an ohm as above

described. Attach one end of it to a brush pressing against the armature. From a single secondary cell pass a current through a resistance of about 100 ohms, in series, with the low resistance and the armature. The current strength flowing on this circuit is therefore everywhere the same. To the ends of the one-hundredth ohm resistance apply wires in connection with the terminals of a high resistance reflecting galvanometer, and note the deflection produced. This deflection is proportional to the fall of potential between the ends of the resistance. Do the same with the armature, testing the difference of potential between two opposite sectors of the commutator. To ensure accuracy, the armature should be turned round into several positions, and the mean of all the observations taken. The resistances of the armature and of the one-hundredth ohm resistance are directly as the deflections of the galvanometer, and hence the resistance of the armature is at once known.

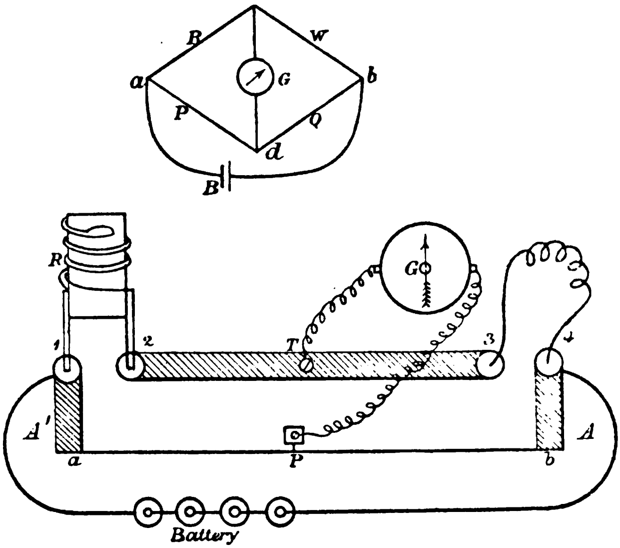
The same method may be adopted for measuring the resistance of short lengths of cable or wire. The accuracy of the test depends, however, upon the current strength remaining the same during both measurements. It can only do this if the total resistance of the circuit is comparatively high, hence the reason for adding the 100th-ohm resistance in series with the others. The well-known Wheatstone's bridge is the most usual appliance for comparing resistances.

As is well known, the method was not invented by Wheatstone, but by Mr. Christie, in 1833.* It consists essentially of an arrangement of six conductors, joining four points. One of these conductors is a battery circuit, and the other a galvanometer. A Wheatstone bridge, suitable for workshop purposes, may be made as follows:—On a board about 4 feet long fasten down a paper scale of inches and tenths, and over the paper scale stretch a fine uniformly drawn German

* See Wheatstone's Scientific Papers, p. 129, published by the Physical Society of London.

silver wire. The ends of the wire are soldered to thick copper strips A A′ (see Fig. 58), which terminate in mercury cups 1, 4. Between these extreme cups there is a strip of

Fig. 58.



Wheatstone's Bridge.

copper B about 1 inch wide and one-sixteenth of an inch thick, having mercury cups 2, 3, at its ends. There is also a terminal T soldered in the middle.

Prepare five resistance coils, as described above, of approximately 1, 5, 10, 50, 100 ohms, and let them, if possible, be adjusted by some one who possesses known standards. These coils are made so that their copper legs will dip into the mercury cups 1, 2. A battery of half-a-dozen Leclanché cells is also needed, and a delicate astatic galvanometer.

Insert the standard coil in the cups 1, 2, the ends of the wire whose resistance is to be measured in the cups 3, 4. Connect the battery to the cups 1, 4, one terminal of the galvanometer to the terminal T, and take the other end of the galvanometer wire in the hand, and just touch it to some point on the German silver wire. The galvanometer will in general make a deflection, but by sliding the galvanometer wire along the German silver wire, a point P can be found at which there is no deflection right or left. When this is the case, note the lengths of the German silver wire P*a* P*b* on either side of the point of no current. Then, as length P*a* is to length P*b*, so is the value of the standard of resistance R to the resistance of the wire to be measured to. Hence a simple rule of four sum gives us the required resistance.

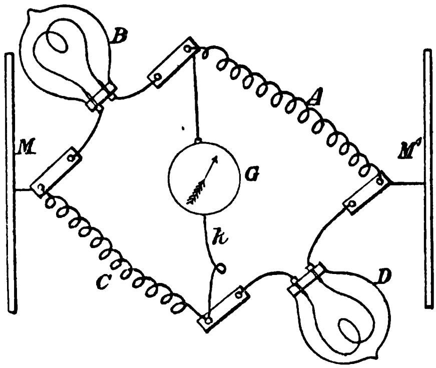
To understand the reason for this rule, we see, if we refer to the upper diagram in Fig. 58, that the battery current from B entering at *a* has two routes open to it to pass to *b*, one by the resistances R and W, and the other by the resistances P and Q. Down each of these paths there is a gradient of pressure or fall of potential, and when the "bridge is balanced," that is when a point is found on each path, such that no current will flow between them when they are connected by a galvanometer, it follows that the pressure at *c* is equal to that at *d*. Now the fall in potential in passing from *a* to *c* along R must be equal to the fall in potential in going from *a* to *d* along P, and similarly the fall of pressure from *c* to *b* is equal to that from *d* to *b*. Now just as in the first method given of measuring resistance we see that the ratio of the resistance R to resistance W is equal to that ratio of fall of potential between *a c* and that between *c b*, and this ratio is equal to that of fall of potential between *a d* to that between *d b*, which in its turn is equal to the ratio of the resistance P to Q. Accordingly when the bridge is balanced we have the proportion—

As resistance R is to resistance W, so is
resistance P to resistance Q,

and any three of these being given we can find the fourth.

There is an ingenious application of the Wheatstone's bridge principle, made by Mr. Edison, in the construction of an appliance for indicating whether the electromotive force of a dynamo driving lamps is constant. A bridge is formed (see Fig. 59), having one pair of arms of German silver wire, and one pair formed of two carbon filament lamps.

Fig. 59.



Edison's Bridge for preserving Constant Electromotive Force on Electric Light Circuits.

M M' are the mains, and the current from these passes by the double circuits A B, D C. G is a galvanometer, and a key, *k*. The resistances are so adjusted that when the proper electromotive force is maintained between the mains M M' the bridge is balanced and no deflection is found when the key *k* is depressed. If the electromotive force rises, then more current will flow across the bridge. This current will heat both the carbon filament and the German silver wire, but whilst heat increases the resistance of a metal, it

decreases that of carbon, hence the resistance of arms A and C is increased but that of B and D is decreased, hence the balance is upset and the galvanometer deviates in one direction. If on the other hand the electromotive force decreases the galvanometer deviates in the other direction. Hence the stability of the galvanometer needle is a very delicate test of constancy in the electromotive force between the mains.

§ 52. We have already seen that the energy which is being dissipated per second in a conductor conveying a current between any two points, is measured by the product of the strength of the current and the difference of pressure between those points, and that if that current is measured in ampères and the difference of potentials in volts, the product is the activity measured in watts, or the energy-dissipation per second in joules. An instrument which measures in one operation the activity in a circuit is called a watt-meter. The best known of these is Siemens' watt-meter, which is an instrument resembling externally the current dynamometer already described. The principle upon which it is based is very simple. A rectangular coil of many turns of very fine wire is fixed against the upright support. (See Fig. 60.) The ends of the coil are connected to the ends of the circuit in which it is desired to measure the activity. Since the resistance is large compared with the resistance of the circuit in which we are measuring the activity, it follows that the current flowing in this fine wire coil is always proportional to the difference of potential between the ends, or to the fall in volts along the circuit we are considering.

Outside this fixed coil there is another movable coil consisting of one or two turns of thick copper wire or strip. This thick coil is suspended by a spiral spring, so that its plane is always kept at right angles to the plane of the fixed fine wire coil. The ends of the movable coil terminate in wires which dip into mercury cups, in such a way as to

leave the coil free to move within certain limits and yet enable the current to pass into it. The terminals of the thick

Fig. 60.

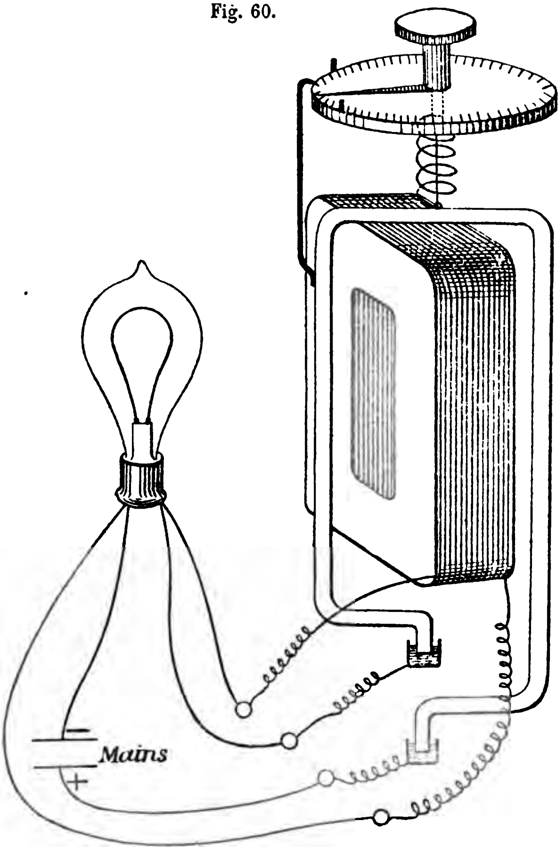


Diagram of Siemens' Watt-meter.

coil are so connected with the circuit in which we are measuring the activity that the whole main current goes through it.

When these connections are made, there is an attractive force between the two coils tending to pull them round into the same plane with each other—the current in the thick coil being nearly equal to that in the conductor, and the current in the fine wire coil being proportional to the difference of potential or volts between its ends. Hence the attraction between the coils is proportional to the product of the current and fall in volts, along the circuit, that is to the activity or horse-power being spent in the circuit. The attraction between the coils is measured by the torsion which must be given to the spring to bring back the movable coil to its position at right angles to the other. Each instrument is accompanied by a table which shows at once for every given degree of torsion of the spring, the activity in watts corresponding.

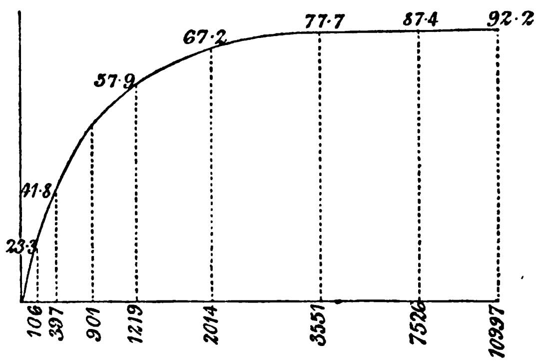
We can employ such a watt-meter in conjunction with a voltmeter to measure the current in a conductor, conveying a continuous current. For if we measure the activity in watts, and also measure independently the fall in volts along the conductor by means of the voltmeter, then the quotient obtained by dividing the watts by the volts gives the current in ampères.

We cannot apply a watt-meter of the type just described, which is adapted for measuring the activity of continuous currents, to measure the activity of alternating currents. The reason for this is as follows: The fine wire coil, consisting of a great many turns of wire, has a very high coefficient of self-induction, and the effect of this self-induction upon the rapidly alternating waves of current which are sent through it when in connection with the ends of a circuit traversed by alternate currents, is to oppose a spurious resistance which makes these waves of current not only less deep, but retards also the time when they come to a maximum. Accordingly the mean current through the coil is diminished by the effect of the self-induction, and as a consequence the

attraction between the fixed and movable coils is less than it would be if there were no self-induction. The indications given by the watt-meter are lower than corresponds to the real measure of the activity. This may partly or nearly altogether be overcome by the device of making the fine wire coil of a very few turns of wire, but supplementing its resistance by an extra coil in series with it outside the instrument, which coil is wound double, as described in the case of resistance coils. The co-efficient of self-induction of the fine wire circuit may in this way be made very small, and then the readings of the instrument can be taken to be very approximately proportional to the activity expended in the circuit to which it is connected.

§ 53. Employing such an alternate current watt-meter we can make very approximate measurements of the ratio of the

Fig. 61.



Curve showing Efficiency of a Secondary Generator at Various Loads.

energy supplied per second to a secondary generator to that which is delivered by it, and estimate therefore the efficiency of such a transformer. Experiments made by the writer on a ring-shaped secondary generator at different lamp loads are tabulated below, in the form of a curve. (See Fig. 61.) The

horizontal distances represent activity in the secondary circuit, and the ordinates represent the percentage of total energy supplied, which appears as electric energy in the secondary circuit at different loads, corresponding to a certain out-put in the secondary. It will be seen that the efficiency of such a secondary generator increases with the load, and at full load about 7 or 8 per cent. of the energy supplied is absorbed in producing local or eddy currents in the iron core, and in magnetising and de-magnetising it. The diagram is not drawn to scale, but intended just to indicate how the efficiency of conversion increases with the load. The horizontal distances represent the activity in the secondary circuit in watts, and the numbers on the curve the percentage of the activity in the primary circuit which appears as activity in the secondary at the various out-puts denoted on the horizontal line.

Voltmeters and watt-meters have been designed by the author in conjunction with Mr. Gimingham, in which the same dynamometer principle is employed as in the Siemens watt-meter, with the modification of making the thick wire coils fixed, and the fine wire coils movable, and using as a restoring force the torsion of a steel chronometer spring.

LECTURE VIII.

§ 54. The subject to which we must next direct attention is that of the electro-chemical generation of electric current, and discuss a few of the points involved in the theory and construction of primary and secondary batteries as sources of electric current and standards of electromotive force. The popular notion of a secondary battery as a contrivance for storing up electricity is quite erroneous. Energy can be stored up, but not electricity, and hence if the term "accumulator" is used, it should be in the sense of an accumulator of energy. It is not very easy to draw a distinction between what should be properly called primary and what should be called secondary batteries. In both forms energy is accumulated in a manner capable of being transformed into electric current, and in both this ultimately depends on chemical attraction; but in the forms of battery, usually called secondary, the chemical processes are such that they can be conveniently and effectively reversed by an external source of current, and so put back the elements into an active condition, without very serious loss of available energy in so doing.

The one fundamental fact which includes all the rest, and on which the electro-chemical generation of current depends is, that if a plate of metal is placed in a liquid of that class we have previously called an electrolyte, there is a difference of electrical condition produced between them of such sort that the metal either takes a lower or a higher electrical potential than the liquid, according to the nature of the

metal and the liquid. If two different metals are placed in one electrolytic liquid, then there is a difference of state produced between them, such, that if joined by a wire outside the liquid a current of electricity traverses this wire. This current proceeds in the liquid from the metal which is most acted upon chemically to that which is least. As the whole theory of galvanic action is still, in spite of half a century of discussion, involved in much dispute, we shall not enter on theories, but simply examine for ourselves the elementary facts.* Let us place in the lantern the glass cell used in our experiments on electrolysis, and fill it with a dilute solution of sulphuric acid in water, say one part of acid to twenty of water. Into this liquid we place a rod of perfectly *pure* zinc. No action is seen to take place. Pure zinc is insoluble in dilute sulphuric acid. Side by side with the zinc we place a rod of silver, not touching it. There is no visible change either in the zinc or the silver. Nevertheless there is an electrical difference between them, and if tested by a voltmeter it would be found that there is a force tending to urge round a current of electricity from the zinc to the silver through the liquid, with an electromotive force of something like one volt.

If we bring the rods near together, so as to touch one another, either inside the liquid or outside, copious bubbles of hydrogen gas will appear to stream off from the silver. At the same time it can be shown that the zinc rod begins to dissolve, and entering into combination with the acid radicle of the sulphuric acid, forms sulphate of zinc.

The circulation of the current and the chemical actions are so related that one cannot take place without the other. That difference of quality, in virtue of which zinc and silver placed in dilute acid can thus give rise to an electric

* The most valuable *résumé* of the whole theory of galvanic action yet published is Dr. Lodge's paper, read before the Society of Telegraph Engineers, vol. xiv. p. 187, 1885.

current, is called their electro-chemical difference, and the zinc is said to be electro-positive to the silver in dilute acid. There is a perplexing nomenclature in use by which the silver plate or its analogue is called the electro-negative, or negative element or plate. It is yet called the positive pole of the combination.

Two electro-chemically different metals placed in an electrolyte constitutes what is called a galvanic cell or couple. If we select two different metals, which are in the natural and ordinary sense unlike, then the combination is called a primary galvanic element. We may, however, proceed in another way. Place in the lantern cell two small plates of platinum. Pass a current through from one to the other; streams of bubbles of oxygen gas ascend from one plate, more copious bubbles of hydrogen gas come off from the other. After a few minutes stop the current. The plates still remain swathed in a clothing of adherent gas films and bubbles. Connecting these plates, which are now said to be *polarised,* with a galvanometer, we find a transitory current of electricity circulating in such a direction as to show that a platinum plate covered with hydrogen is electro-positive to the one covered with oxygen bubbles. The flow of this current is accompanied by the gradual disappearance of these gas films. We learn, therefore, that we can make two platinum plates electro-chemically different by using them as electrodes or plates, wherewith to decompose dilute sulphuric acid, and that such electro-chemical difference is transient, and that after yielding a current for a few seconds when placed in dilute acid they soon become neutral again. Such a combination of two plates of similar metals which have been rendered electro-chemically different by sending a current from one to the other, when immersed in an electrolyte, is called a secondary galvanic couple or secondary cell.

We owe it to the extensive researches of Gaston Planté

that our knowledge of how to make these secondary cells has been vastly increased of late years.

By trying plates of all kinds of metals he was led to the conclusion that lead is the best metal to use. We place in our cell, full of dilute sulphuric acid, a pair of lead plates, and send the current through the liquid from one to the other for a few minutes. Although two lead plates placed in acid are quite unable at first to give rise to a current, yet, when so polarised by the passage of a current through them when placed in a dilute acid, they become electro-chemically different, and on connecting them to a galvanometer, we find they are capable of giving rise to a powerful current. Planté thus showed that the best combination for a secondary cell was that of a pair of lead plates placed in dilute sulphuric acid, and rendered electro-chemically different by the agency of an electric current. We accordingly start with two definitions of what are called primary and secondary galvanic combinations.

A primary galvanic couple consists of two plates of different metals, placed in a chemical solution, which is an electrolyte, or one capable of being chemically decomposed. One of these plates must be more actively attacked by the liquid than the other. The two plates, when joined by a wire, will give rise to a current flowing through the liquid from the plate most powerfully acted upon to that which is least.

A secondary galvanic couple consists of a pair of similar plates, generally lead, placed in one electrolyte, generally dilute sulphuric acid, and which are rendered electro-chemically different by a current called the forming current, which is sent through the liquid from one plate to the other.

§ 55. We proceed to study a few of the defects and arrangements in primary batteries. Let us take a plate of zinc and a plate of carbon, either of the gas retort carbon

cut to shape, or a pressed plate, formed in a manner similar to the arc-light carbons. Place these in a jam-pot filled with dilute sulphuric acid, and connect them by wires with a voltmeter, such as a linesman's detector, capable of showing differences of pressure of fractions of a volt, and not having a resistance of more than three or four ohms. Watch the needle of the voltmeter.

The first effect will be a deflection indicating an electromotive force of something more than one volt. Little by little this deflection will decrease, and as it decreases, we find small bubbles of gas collecting on the carbon. This gas is hydrogen, and this accumulation of gas is called the "polarisation of the negative element." The term polarisation is a most senseless term as here applied, but we take it as in common use. Our examination of the behaviour of the polarised platinum plates showed us that a platinum plate, on which a film of hydrogen gas was deposited, behaved towards another clean platinum plate, just as zinc does to copper, where used as a galvanic couple. That is to say, the deposit of hydrogen upon the plate rendered it electro-positive to platinum not so covered. Accordingly, whereas when we start with the zinc and carbon plate in acid, there is a certain electromotive force urging current round from the zinc to the carbon through the liquid as the current flows, it is accompanied by a chemical decomposition of the liquid, which, by depositing a film of hydrogen gas on the carbon, introduces a counter-electromotive force weakening the original electromotive force. Put in simple language, we may say, that as soon as the carbon plate becomes clothed with a film of adhering hydrogen gas bubbles, that condition, to a great extent, reduces the electro-chemical difference between it and the zinc plate upon which the generation of the electromotive force depends. A single fluid battery, as this is called, has therefore no constancy of electromotive force. To overcome this defect some arrangement has to be adopted

to prevent this deposit of hydrogen upon the carbon plate. The most simple method to adopt is to mix with the dilute sulphuric acid exciting liquid some other chemical body which is a strong oxidising agent, that is, which can combine with and remove the hydrogen as soon as it is liberated on the negative plate. Such substances as bichromate of potash, chromic acid, nitric acid, mixtures of nitrate of soda and strong sulphuric acid, are all strong oxidising agents or bodies possessing the power of parting with the oxygen they contain when in presence of a body, such as hydrogen, capable of combining with it. If some of the red crystals of bichromate of potash are crushed and dissolved in water, and then to this solution about one-tenth its volume of strong sulphuric acid added, we have an exciting solution as employed in what are called bichromate batteries. A plate of carbon and zinc placed in the solution gives a higher electromotive force and more constant current than if simple dilute acid is employed; but although polarisation of the carbon plate is diminished, it is at the expense of another detrimental action. The bichromate solution acts upon the zinc, causing considerable wasteful action, and unless the liquid is in constant motion, the layer of solution next to the carbon plate is soon reduced or deprived of its active oxidising powers, and then polarisation and weakening of the current immediately sets in. A plan generally adopted to keep the oxidising liquid away from the zinc plate where it is not wanted and only does harm, is to place the carbon plate in a porous pot and surround it with the active oxidising liquid. This arrangement, which is called a two-fluid cell, is that adopted in the Bunsen, Grove, and Fuller cell, and in their imitators. The introduction of the porous pot, however, increases the internal resistance of the battery to a certain extent. In the two-fluid cells the solution in which the zinc plate is placed is generally 1 to 10 dilution of sulphuric acid, the other being the oxidising liquid selected

for use. In Grove's and Bunsen's batteries, in which strong nitric acid is the oxidant, the chemical processes reduce this acid to nitrous acid, with evolution of brown fumes, which are oxides of nitrogen. The corrosive and pungent nature of these make it impossible to use the battery except in a draught cupboard or out of doors. The fumes may be to some extent restrained by laying over the battery a cloth well moistened with solution of ammonia. In any form of two-fluid battery yet invented, the oxidising fluid which surrounds the carbon plate sooner or later diffuses through the porous pot or septum, and reaches the zinc. Destructive action on the zinc then begins, and the zinc is uselessly dissolved without effecting anything in the way of generation of electric current.

It is not difficult to show from theoretical considerations that if the electromotive force of a cell measured in volts is multiplied by the number 988,960, the product gives us the utmost theoretical amount of energy that cell can develop in foot-pounds of energy per pound of zinc consumed. Take for example a Grove's cell. The electromotive force of this on open circuit or working through a high resistance, is about 1·95 volts. Hence multiplying by the above number we get 1,928,472 foot-pounds as the maximum energy in the form of electric current capable of being evolved by the solution of one pound of zinc in a Grove's cell. As a matter of fact the solution of one pound of zinc in a battery does not yield more than a portion of this amount of energy in the form of available electric energy in the external circuit. A part of the zinc consumes uselessly in the cell, producing heat in the ordinary way. Another portion of the zinc renders an equivalent in electric energy; but this is wasted in heat in overcoming the internal resistance of the battery, and it is only the remainder that is available in the external circuit. Joule estimated that one pound of zinc dissolved in a Grove's cell and used to raise a weight by means of an

electro-magnetic engine, produced only 331,400 foot-pounds of energy, or only about one-seventh of the maximum theoretical amount equivalent to the zinc consumed.

§ 56. There is a class of galvanic cells in which the polarisation of the carbon plate is prevented by means of metallic oxides. Of these the best known and most useful is the Leclanché cell. In this cell the carbon plate is contained in a porous pot, and packed round with fragments of gas-retort coke and manganese oxide. This peroxide of manganese is a substance rich in oxygen, and it readily parts with the oxygen when in presence of carbon, having hydrogen deposited on it and absorbed by it. The manganese thus serves as a depolariser to remove the hydrogen which would otherwise create a counter electromotive force, by accumulating on the carbon plate. It cannot, however, do this at any great rate. Hence if a battery is formed consisting of a plate of zinc, and a carbon plate packed round as described, the two being immersed in an electrolyte such as dilute acid, we have a galvanic combination which is admirably adapted to furnish small currents of electricity or larger currents with intervals of rest, but which is not adapted to furnish large currents of constant electromotive force. It is most usual to charge the cell with a solution of sal-ammoniac. This salt, however, has a great tendency to "creep" over and cover the outside of the cell with a mass of crystals. This objectionable feature shows itself most when the cells are kept in a warm place. We may, however, instead, employ a very dilute solution, say 1 to 40, of sulphuric acid in water. The zinc should be very pure and amalgamated by rubbing over with pure mercury. There is then very little wasteful action upon the zinc and the crystallisation and "creeping" of the sal-ammoniac is avoided. These cells are, of all others, the best for electric bells and other similar intermittent work.

Another cell of a similar character, but of much greater

power, is formed with oxide and peroxide of lead. Ordinary red lead, or minimum, is made into a stiff paste with dilute sulphuric acid, and the mixture moulded round a lead rod. When dry, this resembles a candle of which the wick is a lead wire and the tallow replaced by oxide of lead. This "candle" is then made the positive pole or electrode in a decomposing cell containing dilute sulphuric acid, and the other or negative pole is an ordinary lead plate. An electric current is then sent through from the positive to the negative pole. The electrolytic oxygen which is liberated at the positive pole, converts the red lead into peroxide of lead, and this process of "forming" must go on until gas bubbles come off freely. When this is the case, the "candle" can be removed and placed in a cell filled with 1 to 10 dilute sulphuric acid, and having a zinc plate opposed to it. Such a cell of zinc, sulphuric acid, and peroxide of lead on lead, has an electromotive force of about $2\frac{1}{2}$ volts, and furnishes a strong and steady current until the peroxide of lead is all reduced by the hydrogen which is liberated on its surface. It has then to be renewed as before by "reforming." *

§ 57. The typical cell for standard purposes is the Daniell cell. A vessel is divided into two parts by a porous partition; on one side is placed a solution of sulphate of zinc and in it a zinc plate; in the other a solution of sulphate of copper, and in it a copper plate. We have then the Daniell cell. When the circuit is closed by a wire joining the plate the zinc dissolves in the sulphate of zinc, and at the other end of the battery copper is deposited out of the sulphate of copper upon the copper plate. There is therefore a complete absence of polarisation. There is no falling off in electromotive force as long as the solutions maintain their strength, and the battery is a constant one. The battery is made up in various forms. For telegraphic

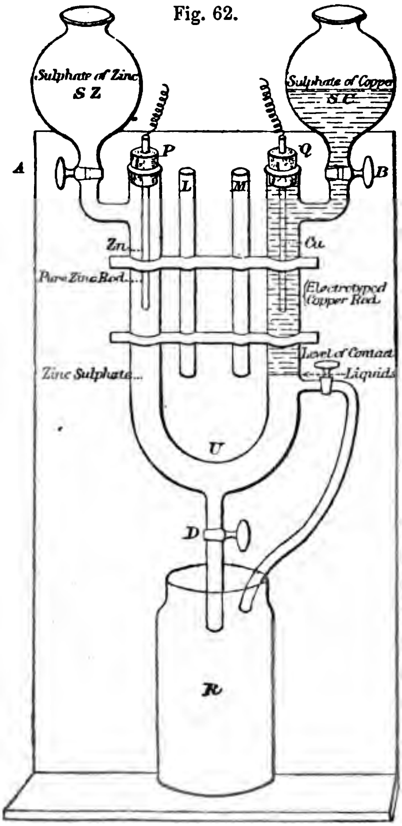
* The author has been shown very effective cells made in this manner by Mr. J. W. Swan.

purposes the two solutions are separated by a porous plate or division. In Sir W. Thomson's form, gravity is made use of to separate the liquids. The copper plate is placed at the bottom of a flat dish. It is covered with a layer of saturated solution of sulphate of copper having a supply of blue crystals of the salt spread over it. On this is floated a lighter layer of sulphate of zinc, and suspended in this is a zinc plate. The abolition of the porous plate diminishes the internal resistance considerably. Considerable attention has been paid to the conditions under which the electromotive force of a Daniell cell is constant or variable with the object of employing it as the standard of electromotive force. In order to make measurements of current and electromotive force by means of the potentiometer method, we require to have some standard of electromotive force. Extensive experiment has shown that there are only two galvanic combinations which are capable of affording what is required. These, if not used for sending any but very small currents, do give a constant difference of potential between their poles, and a constant electromotive force when acting in a circuit of high resistance. These combinations are the normal Daniell's cell, consisting of zinc, sulphate of zinc, sulphate of copper and copper, and the Clarke's cell, consisting of mercury, sulphate of mercury, sulphate of zinc, and zinc.

Commencing with the standard Daniell, it may be formed in the following way:—A large U-tube, about $\frac{3}{4}$ inch diameter and 8 inches long in the limb, has four side tubes. (See Fig. 62.) The two top ones, A and B, lead to two reservoirs Z and C, and the bottom ones C and D are drainage-tubes. These side tubes are closed by glass taps. The whole is mounted on a vertical board, with a pair of test-tubes between the limbs. Suppose, now, a Daniell's cell is to be formed with solutions of zinc sulphate and copper sulphate, and that the zinc sulphate solution is the

denser. The left-hand reservoir S Z is filled with the zinc solution, and the right-hand reservoir S C with the copper

Fig. 62.



Standard Daniell's Cell.

solution. The electrodes are zinc and copper rods, Zn and Cu, passed through vulcanised rubber corks, P and Q, fitting air-tight into the ends of the U-tube.

The operation of filling is as follows:—Open the tap A and fill the whole U-tube with the denser zinc sulphate solution; then insert the zinc rod and fit it tightly by the rubber cork P. Now, on opening the tap C the level of the liquid will begin to fall in the right-hand limb but be retained in the closed one. As the level commences to sink in the right-hand limb, by opening the tap B copper sulphate solution can be allowed to flow in gently to replace it; and this operation can be so conducted that the level of demarcation of the two liquids remains quite sharp, and gradually sinks to the level of the tap C. When this is the case, all taps are closed and the copper rod inserted in the right-hand limb.

It is impossible to stop diffusion from gradually mixing the liquids at the surface of contact; but whenever the surface of contact ceases to be sharply defined, the mixed liquid at the level of the tap C can be drawn off, and fresh solutions supplied from the reservoirs above.

In this way it is possible to maintain the solution pure and unmixed round the two electrodes with very little trouble; and the electrodes, when not in use, can be kept in the idle cells or test-tubes L and M, each in its own solution. In making experiments concerning temperature, the whole U-tube can be immersed in a vessel of water or ice up to nearly the top of the reservoirs, and the temperature in the solutions taken by means of a thermometer passing through the rubber cork. Each of the electrodes can be removed for examination or change without in the least disturbing the surface of contact of the solutions. If experiments are being made in which the sulphate of copper solution is the denser, the position of the solutions is interchanged. The bottle R serves to collect the waste solutions.

The electrodes are made of rods of the purest zinc and copper, about 4 inches long and $\frac{1}{4}$ inch diameter. The zinc found most suitable is made from zinc twice distilled and

cast into rods; the copper prepared by electro-depositing on a very fine copper wire, until a cylinder of the required thickness is obtained.

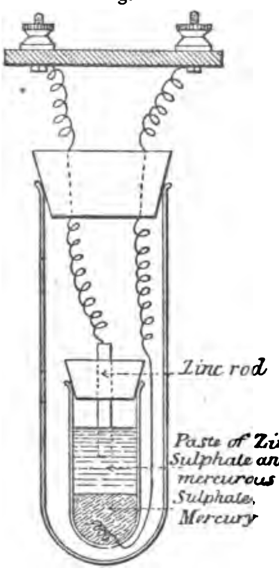
The solutions required for this standard Daniell cell must be made up with the greatest care from the very purest re-crystallised sulphate of copper and sulphate of zinc dissolved in distilled water. To prepare the zinc sulphate solution, weigh out 555 grammes weight of the crystals, and dissolve in 445 grammes of distilled water. The resulting solution will have a specific gravity of 1·400, and should be carefully adjusted to this value at 15° C.

The sulphate of copper solution is prepared by taking 165 grammes of the blue crystals and dissolving in 835 grammes of distilled water, so that the solution has a specific gravity of 1·100 at 15° C. These standard solutions are preserved in well stoppered bottles, and when the standard cell is required, the bulb-reservoirs S Z S C are filled with them as described.

The greatest precautions are required to get the surfaces of the zinc and copper ends perfectly pure and clean. The zinc rod should be cleaned with new glass-paper, but not amalgamated. The copper rod must be electroplated with a new fresh virgin surface of copper just before it is used, and not placed in the cell until its surface presents a clean salmon-coloured surface, free from all brown spots of oxide of copper. For this purpose it is convenient to have a little electrotyping cell worked by a single Leclanché cell, and by means of which the copper rod is prepared and transferred to the cell instantly. Any brown spots of oxide upon the copper rod have the effect of raising by 2 or 3 per cent. the electromotive force of the cell. The electromotive force of the cell, when made up with pure zinc rod solutions, as described, and freshly electroplated copper rod, is 1·072 legal volts; and within ordinary limits it is practically independent of temperature.

The effect of any tarnishing of the zinc rod is to lower the electromotive force of the cell. If any of the sulphate of copper solution should diffuse round into the sulphate of zinc, it will show itself by producing a deposit of black copper, or copper in a pulverulent condition upon the zinc rod. The immediate result of this is to lower the electromotive force of the cell about 3 per cent. This standard Daniell is not intended to be used to generate currents, but only to compare electromotive forces by means of the potentiometer described. And it should be carefully set up afresh each time a determination has to be made.

Fig. 63.



Standard Clark's Cell.

§ 58. The most portable and convenient galvanic standard of electromotive force is undoubtedly the cell invented by Mr. Latimer Clark. Lord Rayleigh has devoted great attention to the investigation of this cell, with the double object of testing its permanence and ascertaining with exceptional accuracy the value of its electromotive force. The form in which it is made up by the instrument makers is far from being the best. The most convenient form is as follows:—A glass test-tube, about three-quarters of an inch in diameter and 2 inches long, has a platinum wire sealed through the bottom (Fig. 63). Into this test-tube is poured about half an inch in depth of the purest mercury. It is not enough simply to buy pure mercury. The purest obtain-

able mercury must be redistilled several times in a vacuum, having been purified previously by treatment with strong sulphuric acid mixed with sulphate of mercury. On this pure mercury is poured a paste, made by rubbing up in a mortar pure zinc sulphate and mercurous sulphate with a little zinc carbonate. The chemicals should be mixed dry and thoroughly incorporated, and then enough distilled water added to make them into a thin paste. The zinc sulphate should be kept in excess, so that the paste is saturated with it and some zinc sulphate remains undissolved. This paste having been poured on to the mercury to the depth of about one inch, a small rod of pure redistilled zinc is passed through a stopper made of unvulcanised rubber, and so placed that the zinc rod dips in the paste without touching the mercury. The zinc rod should have a fine copper wire soldered to it, and a similar wire attached to the platinum wire at the base of the tube. This cell so prepared should be supported in a larger test-tube with guttapercha covered wires, which pass through a rubber cork, and terminals should be fixed to the ends of these wires, so fastened to a strip of ebonite that they cannot by any means touch one another. (See Fig. 63.) (See Appendix II.)

Such a cell carefully prepared has an electromotive force of 1·435 absolute volts at 15° C. It must never be allowed to send a current through any resistance much less than 1000 ohms, but is intended to be used with a potentiometer or electrometer for comparing potentials. If carefully made, its electromotive force will be constant for long periods of time. Its electromotive force decreases as the temperature rises, and for cells made as above may be taken as decreasing about ·077 per cent. per degree Centigrade. It may be taken as nearly ·0011 of a volt decrease per degree Centigrade. Hence a rise of ten degrees in the temperature makes a very perceptible fall in the E.M.F. As we have seen, the Daniell cell is not affected by temperature to any

sensible extent over moderate ranges of temperature, and this gives the Daniell one advantage as compared with the Clark. The Daniell cell has, however, not the merit of portability and ever-readiness which distinguishes the mercury cell.

With these standards of electromotive force and those of resistance, we can make any measurement of the three fundamental measureables—current, electromotive force, and resistance—which may be necessary.

§ 59. We return to the consideration finally of secondary cells. We will first follow Planté, in his remarkable series of researches. Taking a pair of lead plates, we place these in dilute (1 to 10) sulphuric acid, and pass a current from some generator, battery, or dynamo through, from one to the other. The plate at which the charging current enters is called the negative plate; the one at which it leaves the cell is called the positive plate. After a time, lift out the plates and examine them. The negative plate is covered with a puce-coloured film. This is peroxide of lead. The positive plate is unaltered. During the time the plates were in the cell, enduring the passage of the current, bubbles of gas could be seen coming off freely from the positive plate. These bubbles are hydrogen gas.

Having formed a film of peroxide of lead on one plate, reverse the plates and use the peroxidised plate as a positive pole, and the unaltered plate as a negative pole. Pass the current for a short time, and then observe the plates. During the passage of the current, we shall at first not see any bubbles of hydrogen from the positive plate. A short reflection will convince you that the reason for their absence is because the hydrogen gas is now being used up to combine with the oxygen of the film of peroxide of lead already on the plate. After a time remove the plates. The clean plate, which was the last negative plate, is now covered with a brownish film of peroxide

of lead. On the other plate the peroxide of lead has been reduced to a grey film of spongy metallic lead, or of lead in a finely divided state adherent to the lead plate. We have thus, by this alternate treatment, converted our two original clean lead plates into two different plates—one covered with peroxide of lead, and the other covered with finely divided lead. If these two plates are now put back into the dilute acid, and connected with a galvanometer, we find that they can give a powerful current of electricity for a short time. The spongy lead, or reduced plate, or positive plate acts like a plate of zinc. Whilst the peroxidised, or red plate, or negative plate, acts like a plate of carbon, when placed in acid. There is an electro-chemical difference between the plates which enables them, when put in dilute acid, to show a difference of potential, or an electromotive force of about two volts, and to afford a current until they are again brought into a similar state. It is thus seen that a lead plate, covered with finely divided lead, is capable of being acted upon by sulphuric acid, and dissolved just as is a zinc plate. Lead in the mass is very slowly acted upon by sulphuric acid and water; but finely divided, or electrolytic lead, reduced from the oxide, is easily dissolved, or acted upon chemically by dilute sulphuric acid. The process of producing a current by means of these secondary plates oxidises the reduced lead, and brings the plates back into a similar electro-chemical state. The amount of current which can be got out of them is determined by the amount of the active material oxide and reduced lead—hence, to get any considerable quantity of current we must increase the quantity of active material. Planté discovered a process which he called "forming," by which the amount of active material can be increased. If the plates are charged one way, and allowed to stand, the peroxide of lead on the negative plate reacts upon the lead plate carrying it, and by a process, which is called *local action*, gives rise to the

formation of sulphate of lead upon that plate, which sulphate of lead is formed at the expense of the lead plate.

To understand how this takes place, let us take a plate of pure zinc and place it in dilute sulphuric acid. It is almost unacted upon. Take it out and dot over it a number of little spots of sulphate of copper. The zinc reduces the salt and forms little patches of metallic copper, which adhere to the plate. Now place this copper-spotted plate in dilute acid. Streams of hydrogen gas bubbles come off from the copper spots, whilst the zinc dissolves and forms sulphate of zinc, which diffuses itself in the dilute acid. Sulphate of zinc is a very soluble salt, and hence the sulphate of zinc formed is being continually removed in solution and fresh formed. How is it that this solution and formation of zinc sulphate now take place? It is because the copper patches form with the zinc, little galvanic couples, and the galvanic action causes the zinc to dissolve and form sulphate of zinc, just as in the case of a simple copper-zinc element in dilute acid.

When a lead plate covered more or less with patches of peroxide of lead is placed in dilute sulphuric acid, a similar local galvanic action goes on, only in this case the sulphate of lead formed being insoluble, remains on the plate and is not rapidly washed away. When the peroxidised plate is left to itself we see that this *local action* forms fresh sulphate of lead out of the lead supporting plate, and hence increases the amount of lead in a state of chemical combination with either oxygen or sulphuric acid. When the current is reversed, this additionally formed sulphate of lead is, with the already formed peroxide of lead, reduced to the condition of spongy lead, and accordingly there is more spongy lead formed than there would have been, if there had been none of the local action going on which formed sulphate of lead out of the solid lead plate. Planté therefore recognised that the mode of operation which must be

followed to obtain a thick deposit of peroxide of lead, and spongy or reduced lead, consisted in subjecting the lead plates to alternate oppositely directed currents, with an interval of rest between. At each rest the quantity of reducible or oxidisable material is increased and the final result is that the whole of one plate will be converted into a slab of peroxide of lead, and the other into spongy lead. As, however, on this condition the plates would fall to pieces, the operation is never pushed so far, but is terminated whilst yet there is a solid backing of lead plates unaltered to carry respectively the peroxide and spongy lead layers, which are closely adherent to them.

The operation of forming active secondary plates out of lead plates is therefore a prolonged and expensive process, owing to the amount of time required for rest and the current required to produce the peroxide and spongy lead. In 1881, Faure conceived the idea of hastening this process very materially, by putting on to the lead plates a covering of minium or red lead, to start with. The red lead is very quickly reduced on the positive plate to a condition of finely divided lead, and on the other it is raised to the condition of peroxide of lead. In addition to this, the covering of red lead finely divided is in a porous condition which allows the current access to its underlying parts, and hence there is in reality a very considerable active surface. Faure's difficulty, however, was in attaching this oxide to the plates. He first simply spread it over the plates and kept it against them by pieces of blanket, but the acid liquid soon rots the blanket and then the oxide falls away. A great step in advance was made by Mr. Swan in inventing the lead grids. Lead plates are cast having multitudinous holes in them, and into these the red lead made into a paste with dilute sulphuric acid is pressed. As made now, by the Electrical Power Storage Company, these holes are made taper from both sides, so that when the oxide is forced in and sets, the

little block of oxide is keyed in by the fact that its shape is that of a double cone, like a dice-box.

The use of the blanket has been abandoned, and india-rubber studs inserted on the plates to act as distance pieces, and keep the plates in the proper position. Moseley's separators are also employed. These are very thin sheets of ebonite, pierced with holes and corrugated, to give them stiffness and permit circulation of the acid. Made in this form, the secondary cell has now assumed a very practical form. The chief defects which had to be overcome were the buckling or bending of the plates, the oxide dropping off the plates, the corrosion of terminals and leakage of cells. The cells themselves are now made best of glass, ebonite, or highly glazed earthenware. The cells should stand in a dry place, and each cell be well insulated. The cheapest and most effective insulation is made by placing a small cylinder of wood, an inch in diameter and an inch high, in a small glass cup. A little pine oil is then poured into the cups and soaks up the wood. On four of these wood pins the secondary cell is placed, resting on the cylinders of wood. The pine oil prevents loss of electricity, by creeping, as its surface remains always dry, and does not harbour dust. Corrosion of terminals is best avoided by having all joints between the cells autogenously soldered, that is to say, the lead is welted to lead without the use of any solder, the gas blow-pipe being employed to melt the joints together.

In the course of his investigations Planté arrived at the conclusion that a great portion of the time of forming might be saved by treating the lead plates with a dilute solution of nitro-sulphuric acid. The object of this being to render the plates porous, and so enable the current to oxidise a greater surface. He states that he is able in this way to accomplish in a few hours, the results which would have taken many weeks to arrive at by the method of reversals

and rest. Existing practical secondary batteries are either constructed according to the method of Faure or of Planté. There are, however, many modifications of Planté's cell which aim at increasing the lead surface whilst keeping the mass as small as possible. In Howell's battery a lead plate is prepared by allowing molten lead to solidify, and at a proper instant draining away the mother-liquor and leaving a mass of adherent lead crystals. Plates cut out of this mass are in structure like rotten ice, composed of adherent crystals, but very porous in general structure. These plates have then to be formed in the manner indicated by Planté.

Apart from the question of cost, the value of a secondary cell as a means of storage of electric energy, is measured by two factors, the life of the cell, and the capacity for energy per pound weight of the cell. Since the outer containing vessel and exciting liquid are generally but a fraction of the total weight of the plates, we may consider in our estimates and numbers the weight of the cell to be the weight of all the plates, positive and negative, including with the plates or grids, the weight of the active material, oxide or spongy lead, with which they are packed. It is found that if a well-formed secondary lead cell is charged, and the electromotive force measured, that the electromotive force is at first something a little in excess of 2 volts, about $2\frac{1}{4}$ volts. A short discharge relieves the cell of this excess above two volts, and leaves the electromotive force tolerably constant at two volts during the remainder of the discharge. This little extra electromotive force is probably due to the presence of electrolytic hydrogen on the positive plate. It is found that on discharging a good cell that its electromotive force will remain very constant until its charge is nearly exhausted. It then begins to fall rapidly. Let us confine our attention to that portion of the discharge period when the electromotive force is nearly two volts. Every coulomb of electricity which runs out under a pressure of two volts

represents two joules of energy, or 1·47 foot-pounds. Every ampère-hour drawn out is therefore represented by 3600 times this, or 5308·5 foot-pounds of energy. Hence, if a cell discharges at two volts x ampères, where x is any number, a discharge at this rate is equal to an activity of $\frac{1 \cdot 47}{550} x$ horse-power. A discharge of 372 ampères from a single cell is equivalent to a rate of work, or to an activity of one horse-power. A cell, therefore, of which the maximum useful discharge is about 370 ampères, is called a one horse-power cell, and this represents a discharge of 550 foot-pounds of energy per second. A cell is, however, rapidly deteriorated if called upon to give out or accept in charging a large current. There is a proper relation between the area of active surface and total strength of current passing into or out of the cell, which is most economical to use. In the case of the secondary cells, as now made by the Electrical Storage Power Company, in which both positive and negative plates are made of lead grids packed with oxide of lead, and then "formed," the charging current is usually about two ampères per square foot of surface of negative plate.

If, for example, a secondary cell is composed of ten plates covered with peroxide of lead, each 11 inches by 10, and eleven plates alternated with those covered with spongy or reduced lead, then the active surface of peroxide on each plate is the double surface equal to 220 square inches, and the whole ten plates afford a surface of 2200 square inches of peroxide, and the proper charging current will be about 32 ampères. In discharging the cells of this type when formed, a rather greater current density can be allowed, namely, one of about three ampères per square foot.

One important element in judging the value of storage-cells is the amount in foot-pounds of the energy which can be stored up per pound weight of plates. In estimating this energy, it is requisite, however, to consider only that amount

over and above the quantity required to raise the electromotive force of the cell up to two volts. Storage cells for lighting purposes cease to give a useful discharge when the electromotive force falls below two volts. We have already seen that one ampère-hour of charge at a pressure of two volts represents 5308·5 foot-pounds.

Cells formed of lead-grids packed with oxide of lead, and then formed, may be taken approximately as possessing a useful capacity of from 25,000 to 35,000 foot-pounds of energy per pound of plates, reckoning both positives and negatives together.

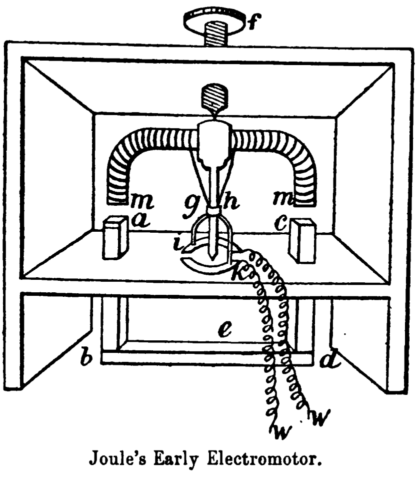
The useful capacity of lead secondary batteries formed on Planté's plan from simple lead plates, is not nearly so great, and may be represented by about 12,000 foot-pounds of energy per pound of plates.

Storage batteries can be made to have very much greater energy storage capacity than the highest of the above figures by increasing the relative weight of the active material relatively to that of the framework, or supporting-plate; but here, as in the case of incandescence lamps, efficiency is not the only factor, duration has to be considered as well, and if the greater specific capacity is obtained at the expense of mechanical strength of the plates, and at the expense of durability, then it is a very doubtful advantage.

LECTURE IX.

§ 60. In the future developments of electric engineering, the electric transmission of power is certain to hold an important position. Nearly half a century ago inventors of a practical turn of mind had permitted their attention to be turned to the consideration of the electric development of power. In 1838 we find the inventive genius of Mr. Joule directed to the ultilisation of the strong attraction of electro-

Fig. 64.



Joule's Early Electromotor.

magnets as a means of making an electro-magnetic engine, in which a current of electricity should give rise to rotary motion of certain parts. One of Mr. Joule's earliest electro-

motors is figured in Fig. 64. The semicircular electro-magnet is caused to revolve round a vertical spindle by the attraction of the permanent magnets underneath, the poles of the electro-magnet being reversed each half revolution. Such an appliance is now a common electrical toy.

Mr. Joule was preceded by others in the same field. The great attractive power of an electro-magnet at short distances, and the extreme rapidity with which its polarity is reversed, readily suggested the idea of employing it for mechanical purposes. Accordingly, as soon as the general principles of electro-magnetism were understood, Professor Henry, Mr. Sturgeon, and others, constructed electro-motors, based on the principle of attraction and repulsion of electro-magnets, and excited by current, generated by batteries consuming zinc as their fuel. Foremost amongst these inventors was Professor Jacobi, and at the time of his experiments expectations were entertained that electro-magnetism might even supersede steam as a means of obtaining mechanical power. Careful investigation, however, showed that these expectations were groundless, at least, as long as electric current could only be generated from primary batteries burning zinc. Joule states that with his electro-magnetic machine every pound of zinc consumed in a Grove's battery produced a mechanical effect equal to raising 331,400 pounds one foot, when the revolving magnets were moving at a rate of eight feet a second. One pound of coal which roughly costs one thirty-sixth as much as a pound of zinc, can be made, by means of a steam engine, to yield 1,000,000 foot-pounds of energy.

This, however, does not show the relative cost of power from the two sources. Taking the case of batteries employing nitric acid as an oxidant, and burning zinc and working an electro-motor having an efficiency of 50 per cent., that is, converting 50 per cent. of the electric energy supplied into mechanical work, the cost of the energy would be some-

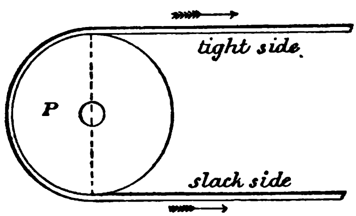
thing approximating to four to five shillings per horse-power per hour.* Using a steam engine and boiler we can reckon upon getting a horse-power hour of energy for about one penny. As long, therefore, as the only plan for obtaining mechanical work from electric current consisted in the use of zinc batteries, the notion of replacing the steam engine was absurd. Even if we reckon as cost of steam power, the wages of attendants, rent and depreciation of plant, nothing yet devised in primary batteries can for a moment enter into competition with it. The practical development of the dynamo has therefore started the problem from a fresh departure, but it has done much more. The evolution of the dynamo, from Faraday's first experiments, carried with it implicitly the improvement of the electromotor. A dynamo belongs to the class of machines which are called *reversible.* This does not mean that it can be run backwards, in the sense in which we speak of reversing in an engine; it means that the transformation of energy, which goes on in the machine is reversible. Most people are aware that a machine of any sort is merely a device for transforming what we call *energy* from one form to another. A steam engine, or a gas engine, transforms the potential energy of fuel and air into the mechanical energy of moving masses. But the transformation cannot be made to take place backwards. Turning round the flywheel of a gas engine will not transform carbonic acid gas and steam back into coal gas and air; or recover the energy in the form in which it first was supplied to the machine. But a dynamo is a reversible engine, and if it were not for friction, it would be a perfect reversible engine. If we rotate the dynamo by mechanical power we generate a current, and if we pass a current into a dynamo we cause it to revolve. If we rotate by hand the armature of a magneto or dynamo

* On this subject, see a useful paper by Mr. W. Peukert, translated in the 'Electrical Review,' May 28, 1886, vol. xviii. p. 493.

machine, and permit the machine to generate an electric current, we experience a resistance to the motion at the moment the external circuit is closed. To overcome this resistance, force has to be exerted, and the energy expended is measured by the product of the "twist" applied to the shaft, and the angle through which the armature is displaced in the time considered.

§ 61. One word of explanation is here necessary as to the mode of measuring work, when expended in causing rotation of a shaft against a resisting action. Let P be a pulley (see Fig. 65), having a belt passed over it. If one side of this

Fig. 65.



belt is pulled more than the other in the direction of its length, then we may consider that when there is no slip, the pulley P is acted upon by two forces, whose directions are tangential to the pulley, and take place in the direction of the arrows. Each of these forces produces a "twist" on the pulley, and the product of the tangential force multiplied by the radius at which it acts, is called the *torque*, or twisting moment of the force. The radius at which each force acts is equal to the radius of the pulley added to half the thickness of the belt. This length multiplied by the pull on the belt gives the *torque* produced by one side of the belt. The two sides of the belt produce oppositely-directed and unequal torques, and the total or resultant torque, or the twist on the shaft, is the difference between the two, that

is to say, it is equal to the difference between the "pulls" on the two sides of the belt, multiplied by the radius of the pulley added to half the thickness of the belt. When a belt drives a pulley, the work done on the pulley per second is numerically equal to the difference of tensions on the two sides of the belt multiplied by the effective circumference of the pulley, and by the number of revolutions per second. The effective circumference of the pulley is obtained by multiplying the diameter of the pulley added to the thickness of the belt by 3·1416. The rate at which work is being done on the pulley is given by the above operation, and if the measurements are in feet and pounds weight then dividing the work done per second by 550 gives the activity expended in horse-power. These statements may be made in another way, viz. that the work done on a pulley by a belt is equal, numerically, to the torque on the shaft, and the angle turned through in the time considered, and the rate of work supply or activity expended is equal to the product of torque and angle turned through per second by the shaft.

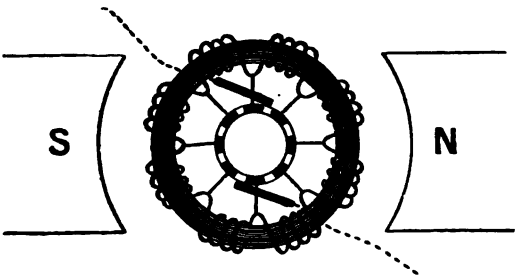
Returning now to the consideration of the dynamo machine, the application of a certain torque to the shaft of the dynamo, and the performance of a certain amount of torsional work, produces a certain electric current in the external circuit, and the electrical output of the machine in any time is measured by the difference of potential in volts between the terminals multiplied by the coulombs of electricity which have been supplied. The rate at which work is being done in the external circuit, or the external activity of the machine, is measured by the product of the current in ampères, and the difference of potentials between the terminals measured in volts. This product represents in watts what some engineers call the electrical horse-power of the dynamo; it is better called the electrical output. The ratio of the electrical output to the work applied to turn the

dynamo round, is called the commercial efficiency of the dynamo. A dynamo electric machine may therefore be defined as a machine by which a certain amount of mechanical energy is transformed into energy of an electric current. The waste of available energy in a good dynamo will not amount to 10 per cent. of the total amount transformed. Now the chief, and by far the most useful characteristic quality of a dynamo, is that the process may be reversed, and that if an electric current is sent through a dynamo it causes it to rotate, and hence electric energy may be transformed back again into mechanical energy of rotation, this transformation taking place with a waste of available energy to the extent of a few per cent. Hence, we have at once opened out to us a mode of transferring mechanical energy from place to place. At one spot transform mechanical energy into electrical energy; that is to say, use a man, or a horse, or a watermill, turbine, or steam engine to rotate a dynamo and create an electric current; lead this current to any other place by means of a copper conductor; pass the current through a dynamo reversed, now called a motor, and cause it to rotate and recover the mechanical energy at this distant spot. We shall proceed to examine some of the details of the general process here sketched.

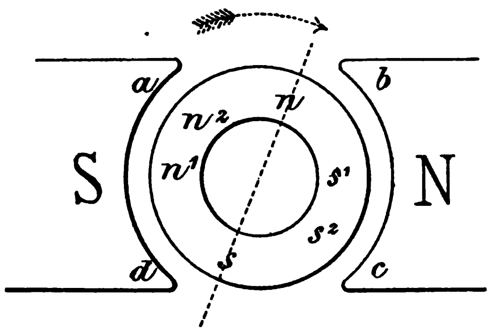
§ 62. The first point which claims attention in considering the dynamo machine as a generator and as a motor is the re-action in each case of the armature upon the field magnets. Let us consider the simple case of a dynamo, constructed with permanent magnets, and with a simple Gramme ring armature. (See Fig. 66.) When the armature is rotating, clockwise, the armature wire is traversed by a current generated in it, which acts upon the iron core of the armature, and magnetises it, creating in it poles as shown in Fig. 67. The direction of the magnetic axis of the armature, or the direction of the line joining its poles so induced, is not perpendicular to the line joining the poles,

or the magnetic axis of the field magnets, but is slightly inclined to this direction; the angle of deviation from the perpendicular being called the angle of lead. The reason

Fig. 66.



Simple Gramme Ring in Field of Permanent Magnets.



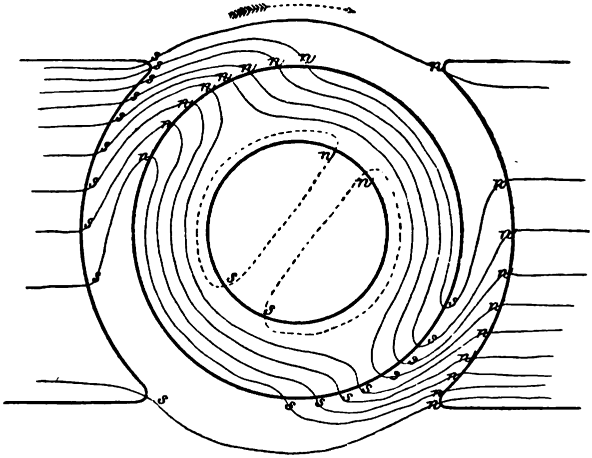
Magnetic Polarity of Gramme Ring in Permanent Field.

for this deviation is as follows:—Suppose the armature to be set in rotation very *slowly*, then it is easy to see that the time of production of the maximum current in any wire of the armature coil will be the instant when, in the course of

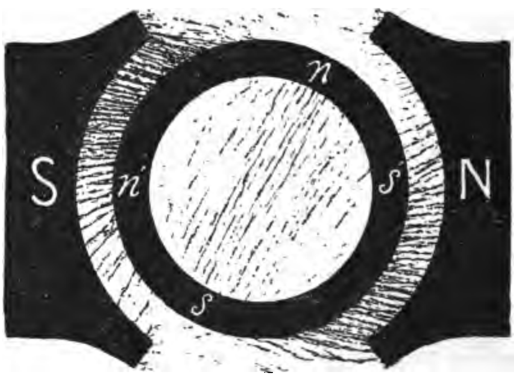
its rotation, it is passing across the line S N, joining the poles of the field magnet (Fig. 66). The magnetic effect of this current on the iron core of the armature will be to induce poles in the core in the direction of an axis *s n*, nearly perpendicular to S N. The joint effect of these two sets of magnetic lines of force, viz. those due to the field magnets, and those due to the poles induced in the armature core by the armature current, will be to produce an oblique resultant magnetic field as shown in Fig. 67. Hence the period of maximum induction in the armature wire will not be the instant of passing across the line S N, but at the somewhat later period of the rotation, when passing across a line inclined to S N, and in advance of it in the direction of rotation. Accordingly the result of this joint effect of the magnetism of the field magnets and the magnetism of the armature core is to shift the direction of the magnetic axis of the armature, and to bring it into the position shown, and this shift or "lead" will, in the case considered, increase with the armature current. We now notice that the poles of the armature are brought into such a position that they partly *oppose* the poles of the field magnets, and hence tend to weaken them; and they will do this the more in proportion as the current in the armature is stronger. This effect is called the re-action of the armature upon the field magnets, and it is important to bear in mind that in a dynamo, whether the field magnets be permanent or electro-magnets, the effect of the magnetism of the armature is to oppose and tend to weaken the magnetism of the fields, and to shift the line of magnetic axis of the armature in the direction of the rotation by an amount called the angle of lead, which varies with and depends on the current which is being induced in the armature coils. Let us now suppose the dynamo to be used as a motor, that is reversed, and consider what in that case are the magnetic conditions of armature and fields. We will suppose the dynamo con-

sidered has its field magnets wound as a shunt to the armature.

Fig. 67.



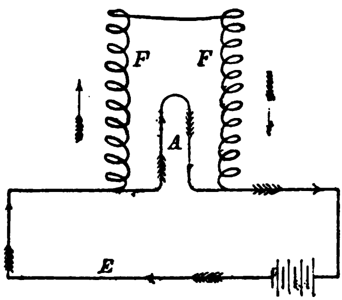
Induced Magnetic Poles and Lines of Magnetic Force through Gramme Ring in a Dynamo.



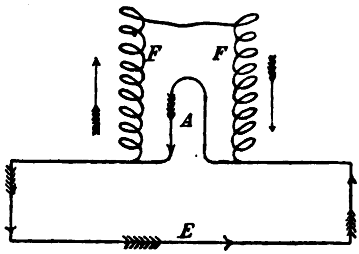
Resultant Magnetic Field in the case of a Gramme Armature Generating Current.

In Fig. 68, the lower figure represents by a skeleton diagram the course of the currents in the field-magnet coils F F, and the armature A, and the external circuit E of a shunt

Fig. 68.



Dynamo as a Motor.

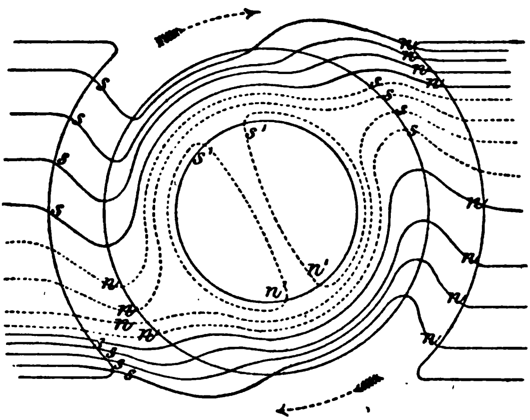


Dynamo as a Generator.

dynamo, supposing the machine to be used as a generator. Let now the current in the external circuit be reversed and sent back into the machine, driving it as a motor. The course of the currents will be as in the upper diagram. We see that the current in the field magnet is in the same direction as before, but that in the armature it is reversed. Consider for

a moment what will be the magnetic condition of the armature. It will have its poles placed, as in the case of the generator, but they will be reversed in position, that is to say, the part of the armature advancing towards either pole piece will have a contrary polarity (see Fig. 69), and hence the poles of the fields and armature will mutually *strengthen* one another. The re-action of the armature on the fields is therefore of an opposite nature in the case of a motor, to

Fig. 69.



Induced Poles in Armature in the Case of Dynamo used as a Motor.

that which it is when the machine is used as a generator. It is not, however, of any advantage that the armature magnetism should re-act in this manner upon the field magnets; on the contrary the most advantageous and desirable condition to attain is, that the magnetic field due to the field magnets alone should be so strong that it is hardly at all distorted by the currents induced in the armature coils. In this case the direction of magnetisation of the

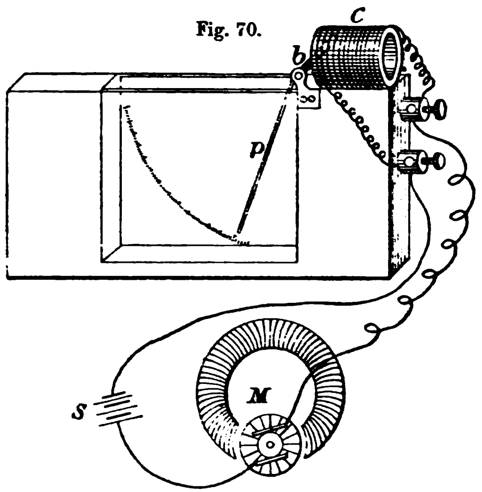
armature, or its magnetic axis, will be very nearly perpendicular to the direction of the undisturbed lines of force of the fields, and there will be no variable "lead," as the outgoing current or load is increased or diminished.

§ 63. We have next to examine another action taking place in the motor. Consider the simple case of a straight wire which is placed in a magnetic field with its length perpendicular to the lines of magnetic force. If a current of electricity be passed through this wire, it will experience a force tending to move it perpendicularly to itself and to the lines of the magnetic field. Imagine the lines of magnetic force to flow horizontally from south to north, and that the conducting wire is laid east and west in a horizontal position and has a current passed through it from west to east, then there will be a force acting on the conductor tending to lift it upwards in a direction perpendicular to the plane. If, however, the conductor is allowed to move under this force, the act of moving across the lines of magnetic force generates in it a current, or tends to generate in it a current which would flow in it from east to west, that is to say, in an opposite direction to the current causing motion. Accordingly, when a conductor is placed in a magnetic field and has a current passed through it from some external source, and is free to move under the action of the electromotive force, the very act of moving induces in it a counter current, or a counter electromotive force opposite in direction to that which causes the motion. This is exactly what happens in the case of a dynamo when used as a motor. The current supplied to it passes, in the case of a shunt-wound motor, partly through the field circuit creating a magnetic field, and partly through the armature. The conducting wires in the armature experience accordingly a force tending to cause them to move across the lines of force of the magnetic field, and at the same time the very motion induces in the armature coils a counter electro-

motive force which opposes and diminishes the current being passed through the motor.

It is important to notice in passing, that the twist or rotating force is communicated to the shaft of the armature through the electro-magnetic force acting on the wire, and not by magnetic attractions or repulsions on the iron core. Hence, in order that a motor may be able to transmit and transform large powers, it is essential that the mechanical arrangement for securing the wire coils on to the armature shall be good. In order to exhibit the production of the

Fig. 70.



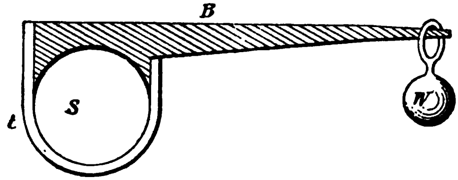
Lantern Ammeter and Motor.

counter electromotive force in a motor when allowed to rotate, the following arrangement has been made. We have here a little motor, called a Griscom motor. From a couple of secondary cells I pass a current through this motor. In the circuit is interposed a current measurer adapted to the lantern. (See Fig. 70.) C is a small coil of wire, and *b* is

a short needle of soft iron, carrying a long aluminium pointer *p*. This needle is pivoted on a support just outside the coil, and in its ordinary position the weight of the pointer makes the needle take an oblique position in the coil; but when a current is passed through the coil the short soft iron needle tends to set its length along the axis of the coil; and the degree to which it is able to do this, in opposition to the weight of the pointer, is a measure of the value of the current through the coil. Placing the lantern ammeter in the lantern, and projecting it upon the screen, we have the greatly enlarged image of the pointer and scale before us. I now hold the shaft of the motor fixed and pass the current from the cells through the motor and ammeter in series. The needle, as you see, takes a certain definite inclination indicating a current of a certain value passing through the motor. I now release the armature and let it spin round; the instant it starts you see the deflection of the needle decrease. This indicates a diminished current. Accordingly, the motor behaves just as if its resistance were suddenly increased the moment it begins to rotate. This apparent increase of resistance is due to the presence of a real counter electromotive force due to the opposing induction created in the armature as soon as it begins to rotate in its field.

§ 64. We may next consider the question of the efficiency of a motor. Let S in Fig. 71 be the end of the shaft of the

Fig. 71.



armature of a motor, and let B be a bar, which by means of a strap can be caused to grip the shaft with a certain force.

On the end of the bar let a weight, W, be hung, of such magnitude that when the shaft is rotating in the direction shown by the arrow, the bar is just kept horizontal. It is easy to see that if the weight is too small, the whole bar will be carried round in the direction of rotation, and if it is too great it will cause the bar to be pulled down into a vertical direction. When, however, the proper weight is adjusted to the bar, such that it preserves the bar horizontal whilst the shaft revolves within the grip of the strap, then there is a state of balance between the torques or twisting forces acting on the bar. In this case the work done in turning round the shaft is at once given, for the work expended during one revolution of the shaft is equal numerically to the weight hung at the end of the bar measured in pounds multiplied by the circumference of the circle of which the bar is a radius measured in feet, and the product is the work in foot-pounds. If this number is again multiplied by the number of revolutions of the shaft per minute, we have the work done per minute, and this divided by 33,000 gives the activity or power being expended in horse-power. Such an arrangement is called a Prony, or friction brake.

Let us suppose then that we take a motor of some kind, and drive it by means of a current supplied from some source of steady electromotive force, say, for example, from secondary cells. Let there be attached also to the shaft of the motor some form of friction-brake, such as the one described, and let an ammeter and voltmeter be arranged to measure the current passing through the motor and the difference of potential between the terminals of the motor. Allow the motor to revolve and adjust the brake to a balance to measure the work given off from the shaft. Measure also the current and E.M.F. between terminals of the motor. The product of the current in ampères and the real E.M.F in volts, divided by 746, gives the rate of supply of work or power electrically supplied in horse-power. The reading of the

brake gives the horse-power yielded by the shaft. The ratio of power yielded to power supplied is called the commercial efficiency of the motor for that speed and load. If the motor is held fast, so that it cannot revolve, and the electrical power supplied to it measured, then we know that the whole of the energy goes to produce heat in the motor, and it is called the dissipated energy. If the motor is allowed to revolve and do work, then over and above the energy dissipated in overcoming the passive or ohmic resistance of the wire, there is an amount supplied which is the absorbed energy.

The whole of this absorbed energy is not, however, realised as available mechanical work on the shaft, because a certain portion is used up in overcoming friction of the shaft in its bearings, and in producing useless eddy currents of electricity in the iron core of the armature. In a fairly well designed motor the frictional resistance to rotation will not be a large item, and hence the two great sources of energy dissipation are that due to electrical resistance of the wires of the armature and magnets, and that consumed in producing useless eddy currents in either the iron core of the armature or other metallic parts, or in the pole pieces of the field magnets. It is even more important to construct a motor on such designs as to prevent the formation of eddy currents in the core than in the case of a dynamo.

In a dynamo, the rotation of the armature causes eddy currents to be generated in the iron core in the same direction as in the conductor proper, with which the core is surrounded. Of course, as the armature is always more or less subdivided or laminated in a direction at right angles to the lines of force, any circulation of currents round the core is avoided, but local currents, which are aptly called eddies, are set up, and, taken as a whole, these eddy currents in the core are in the same direction as the current flowing in the armature wire. In an electromotor, however, the eddy currents, and the currents in the

armature wire are in opposite directions; as, although the E.M.F. set up in the conductor is in the same direction in a motor as in a dynamo, the current in the former is forced through the armature in a direction contrary to the E.M.F. or opposite to its course in a generator. According to the laws of induction, therefore, it will be seen that while in a dynamo the two sets of currents, those in the iron and those in the conductor, tend to oppose and to reduce one another in a motor, they act in such a manner as to mutually assist one another.

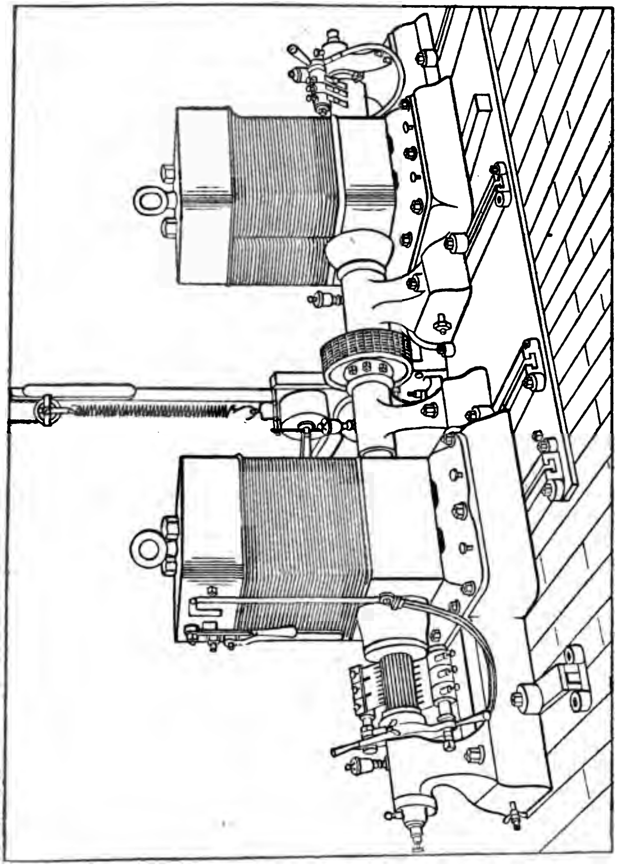
Thus with the strength of field and the current in the conductor and the speed the same in the two cases, it will be seen that in a motor the eddy currents in the iron core of the armature will be greater than in a generator, and, therefore, the heat lost in the former will be more than in the latter.* There is little doubt that this is the cause of the lower efficiency of motors than of generators.

§ 65. Turning now to the consideration of the determination of the efficiency of motors, we shall instance the method recently devised by Dr. J. Hopkinson, by which the efficiency of a machine as a motor and of a dynamo can be simultaneously determined. The method requires two machines of similar construction and equal size. These machines have their shafts coupled together in one line, and a pulley attached at the coupling. (See Fig. 72.) Round this pulley passes a belt which supplies motive power, and the belt passes on its way through a dynamometer of the Hefner Altenech type, which serves to determine the difference of tensions on either side of this driving belt, and hence to deduce the horse-power. In addition, the main terminals of the machines are connected together, so that the current which comes out of one machine, which runs as a generator, goes into the other which runs as a motor. Accordingly it

* See a paper by Mr. W. M. Mordey, on 'The Dynamo as a Generator and as a Motor,' 'Philosophical Magazine,' January 1886, p. 20.

will easily be seen that the machine which runs as a motor is made to rotate partly by a supply of electrical energy from

Fig. 72.



Dr. J. Hopkinson's Method of Measuring Efficiency of a Dynamo and Motor.

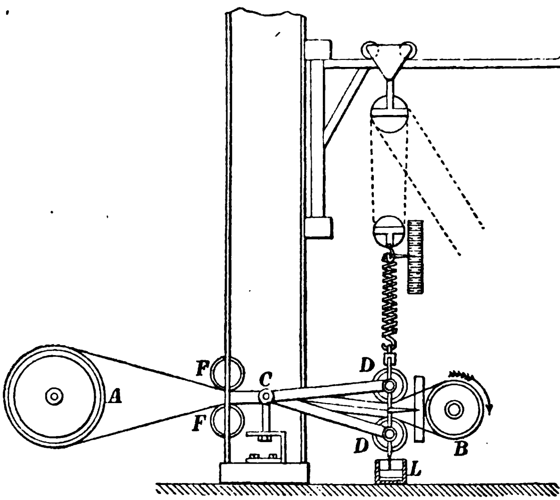
the generator, and partly by mechanical energy supplied from the belt.

The belt, therefore, has only to supply mechanical work equal to the sum of the losses of available energy in the double transformation. The work, therefore, to be mechanically measured is small. The great advantage of this arrangement is the much greater accuracy possible in measuring the numerical value of this work. Suppose, for example, that the efficiency of a motor is being measured in the ordinary way, by measuring the value of the electrical energy supplied to it, and the mechanical energy obtained from it. The electrical measures may be made with great accuracy, but the measurement of mechanical work by a brake-dynamometer is not so easy. An error of 5 per cent. is quite possible, and hence a corresponding error in the value of the efficiency. But in Dr. Hopkinson's method, suppose we are dealing with a pair of dynamos, in which the total loss in the double conversion of mechanical work into electrical and back again reaches 20 per cent., then an error of even 10 per cent. in the measure of this differential work only means an error of 1 per cent. in the efficiency of each machine, generator, and motor. We are thus placed in a position to measure with very considerable accuracy the efficiency of conversion of a motor.

Recent trials with a pair of Edison-Hopkinson machines, built by Messrs. Mather and Platt, have given very high results for this form of machine when used as a motor. The two coupled dynamos were of similar dimensions, each intended for a normal output of 110 volts and 320 ampères at a speed of 780 revolutions per minute. They were both shunt-wound, and having solid wrought-iron magnet cores and field-pieces. The commutators were of copper in forty pieces, insulated with mica. The general arrangement of the dynamometer is shown in Fig. 73. In that figure, B shows the driven coupling of the dynamos. D D the guide pulleys of the dynamometer turning about the fulcrum C,

and supported by springs, the tension of which is read by a pointer against a fixed scale when the index of the dynamometer is brought to its fiducial mark. L is a dash-pot, containing oil to check vibrations. F F are guide pulleys

Fig. 73.



Power-Dynamometer used in Dynamo Tests.

bringing the belt parallel with the dynamometer. The readings of the dynamometer give the difference of the tensions or pulls on the two sides of the driving-belt, and this difference, multiplied by the feet per minute velocity of the belt, and divided by 33,000, gives the horse-power applied on the pulley. In the experiments the electrical energy was obtained from measurements of the difference of potentials at the terminals of the generator and motor, and the value of the current was obtained by passing it through a known resistance and measuring the difference of potentials at the

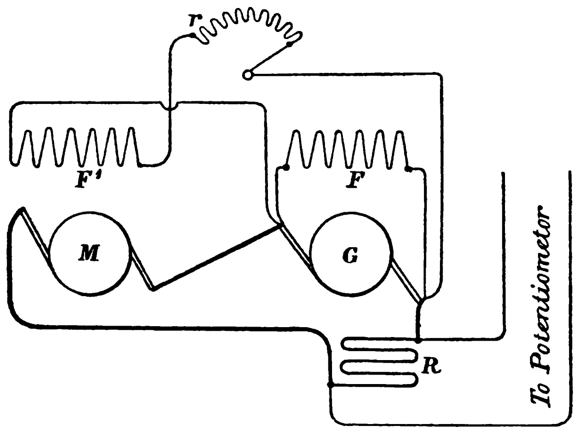
ends of this resistance by means of a Clark's cell and potentiometer. The resistances of the armature and magnets of the two machines were as follows:—

Generator	Armature	0·009947	ohm.
	Magnets	16·93	"
Motor	Armature	0·009947	"
	Magnets	16·44	"

During the experiments a current of about 360 ampères flowed from the generator to the motor.

Fig. 74 shows the general diagram of the electrical connections. These arrangements made, the observations con-

Fig. 74.



Electrical Arrangements as used in Hopkinson's Method of Testing Dynamos.

sisted in measuring simultaneously the electrical energy transferred from one machine to the other, and the balance of power supplied by the belt driving the pulley on the common shaft. The results were as follows:—

E.M.F. at terminals of generator	= 110·12 volts.
Current	= 358 ampères.
Current through generator magnets	= 6·5 „
„ „ motor „	= 5·36 „
E.M.F. at terminals of motor ..	= 107·33 volts.
Speed of machines	= 764 rev. per min.
Power transmitted by belt ..	= 6602 watts.
	= 8·850 h.p.

Hence

Total power given to generator	= 42917 watts.
	= 57·53 h.p.
Power lost in internal friction of armature core	= 831 watts.
	= 1·11 h.p.
Power lost in generator magnets	= 716 watts.
	= ·96 h.p.
Power lost in generator armature	= 1360 watts.
	= 1·823 h.p.

And therefore

Commercial efficiency	= 93·23 per cent.
Loss in core	= 1·94 „
„ magnets	= 1·66 „
„ armature	= 3·17 „

Similarly for the motor.

Total power given to motor ..	= 38886 watts.
	= 52·13 h.p.
Power lost in internal friction of core	= 831 watts.
	= 1·11 h.p.
Power lost in motor magnets ..	= 472 watts.
	= ·63 h.p.
„ „ armature ..	= 1275 watts.
	= 1·70 h.p.

And therefore

Commercial efficiency of motor ..	=	93·37 per cent.
Loss in core	=	2·14 „
„ magnets	=	1·22 „
„ armature	=	3·27 „

It will be seen that these figures do not take into account one or two minor losses which tend to diminish the efficiency slightly, such as the friction of the bearings and the bending of the belt round the driving-pulley. These losses depend to some extent on lubrication and on the kind of belt used. In order to obtain approximately this loss, the dynamos were run at proper speed, without any load, and the dynamometer reading taken. The driving-engine was then reversed and the dynamometer again noted. The difference of these readings is twice the friction of the two machines and twice the work done in bending the belt. The loss for one machine was found to be ·84 horse-power running at 800 revolutions. Taking into consideration the variations in friction of the belt where transmitting full power to drive one dynamo, experiment showed a loss of ·73 per cent. When these losses are deducted from the efficiency above given, the commercial efficiency is seen to be 92·5 per cent. for the generator, and 92·6 for the motor. Hence we must acknowledge that the dynamo is not only a most perfect machine for transforming mechanical work into electric energy, but that it is nearly a perfect reversible engine, and can perform the operation of transforming back with just as great economy electrical energy into mechanical power. We see from the above figures that the double conversion, or the transmission of mechanical work through the mediation of electrical energy is performed with an economy of about 85·5 per cent. If instead of these two dynamos having their shafts coupled they had been separated by any distance, but electrically connected by a cable of such

resistance as to waste about 10 per cent. of the energy transmitted through it, we see that the coupled dynamos would form a means of transmitting to a distance over 75 per cent. of the mechanical energy applied to rotate one of them. Since the publication of Dr. Hopkinson's method of obtaining the efficiency of a coupled dynamo and motor, other writers have suggested that the whole of the measurements may be made *electrical* by supplying the difference of power by a third dynamo or some secondary cells inserted in the circuit, and by this means get rid of any mechanical measurement of power at all. The electrical transmission of power with very high economy is therefore an accomplished fact. Electrical transmission of power has in many respects great advantages over the transmission of power by belts, shafts, water, or compressed air. An electrical conductor is a perfectly flexible thing, which can be bent or carried round corners and tapped where ever desired. Moreover, it is motionless, and transmits large amounts of energy without being itself visibly in motion. The dynamo as a generator, has already revolutionised electrical science, and the dynamo as a motor is destined to accomplish great things in addition in the reverse transformation of electric energy into mechanical work.

APPENDIX I.

THE following paper contains an account of Mr. Shelford Bidwell's recent interesting investigations on magnetisation of iron.

*On the Lifting Power of Electro-magnets and the Magnetisation of Iron.**

The author believes that no very recent investigations have been made with reference to the maximum lifting-power which an electro-magnet is capable of exerting, the experiments conducted by Joule between the years 1839 and 1852 still forming the basis of most of our practical knowledge on the subject.

It is a matter of common experience that if an electro-magnet be excited by a gradually increasing current, a limit is soon reached beyond which the ratio of increase of sustaining power to increase of current becomes rapidly smaller, and it has generally been assumed that this ratio continues to diminish indefinitely, so that an infinite current would not impart to a magnet much greater lifting-power than that which it possesses when an approach to saturation is first indicated.

Joule, after having shown by experiment that the power of an electro-magnet varies as its sectional area, expressed the opinion that "no force of current could give an attraction equal to 200 lb. per square inch," and much later Rowland stated, as a probable result of his well-known researches in

* By Shelford Bidwell, M.A., LL.B., F.R.S. Communicated by Lord Rayleigh, Sec. R.S., to the Royal Society. Read May 20th.

magnetic permeability, that the greatest weight which could be sustained by an electro-magnet with an infinite current was, for good but not pure iron, 177 lb. per square inch, or 12,420 grams per square centimetre of section.

It has long been known that when an iron rod is magnetised its length is in general slightly increased. Some experiments on this effect of magnetisation, an account of which has been given in two papers recently communicated to the Royal Society, show that if the magnetisation is carried beyond the point at which the magnetic elongation of the rod reaches a maximum, the length of the rod, instead of remaining unchanged, steadily diminishes, the curve expressing the relation between the length and the magnetising force descending in a perfectly straight line which within the limit of the experiments shows no tendency to become horizontal. Some further experiments (not yet published) have also been made with rings of iron instead of rods, and effects of precisely the same character were obtained. The diameter of a ring was found to be increased by a comparatively small magnetising current, and diminished by a strong one. Now the retraction in question does not begin to occur until after the stage of magnetisation, loosely called the "saturation point," has been passed, when, according to the common belief, the magnetisation of the iron has practically reached a limit, and is not sensibly affected by any further increase of the magnetic force; and hence arises a difficulty in accounting for the phenomenon. The most obvious method of explaining the retraction is to assume that under the influence of increasing currents the magnetic attraction of the particles of the iron towards one another is increased, and thus the rod becomes compressed. But this cannot be the case if the magnetic condition of the iron has become constant and independent of the magnetising current. And a similar objection will apply to any hypothesis which assumes (as, perhaps, all must) that some property of the iron dependent upon its magnetic condition varies in a

sensible degree with the magnetising force after the "saturation point" has been passed.

The author was led by considerations of this nature to the belief that it would be desirable to make some experiments with the view of ascertaining whether the lifting power and general magnetic condition of an iron rod are as nearly uniform under strong magnetising forces as is commonly supposed. Two pieces of apparatus were therefore prepared. The first consisted of a rod of iron hooked at each end and divided transversely in the middle, together with a long solenoid, inside which the divided rod could be placed. The second was an iron ring cut into two equal parts, each of which was encircled with a coil of insulated copper wire. In both cases the construction was such that an intense magnetic force could be produced with comparatively small battery power. The divided ring could be used either as a semicircular electro-magnet with a semicircular armature, or, if the current were passed through both coils, as two semicircular electro-magnets.

Merely to test the hypothesis of Joule and Rowland, two or three determinations were made of the weight which could be sustained when the current was caused to circulate around one only of the semicircles, the other being used as an armature. With a current of 4·3 ampères the weight supported was 13,100 grams per square centimetre of surface; with a current of 6·2 ampères the weight supported was 14,200 grams per square centimetre. In the latter case, therefore, the lifting power exceeded that which both Joule and Rowland considered the greatest that could be imparted to a magnet by an infinite current. Had it been worth while to incur the risk of injury to the insulation of the coil, there is no doubt whatever that by applying stronger currents the lifting power might have been carried still further—for there was no indication that a limit was being approached. But it was of greater interest to study the effects produced when both portions of the ring or of the

rod were under the direct influence of the magnetising coil.

The first experiment was made with the divided rod. One portion was supported by means of its hook in a vertical position; a scale-pan was attached to the hooked end of the other portion, and the flat ends of the two were brought into contact and surrounded by the solenoid. Currents of gradually increasing strength were then caused to pass through the solenoid, and note was taken of the greatest weight which could in each case be placed in the scale-pan without tearing asunder the ends of the two rods. The general results are briefly as follow:—When the intensity of the field at the junction had reached about 50 C.G.S. units, the weight supported was nearly 7000 grams per square centimetre of the section of the rod. After this value was exceeded it became quite evident that the weight which could be sustained was increasing more slowly than the magnetising current, and the proportionate increase became rapidly smaller as the current was made stronger. This state of things continued until the intensity of the field was about 270 units, when the weight supported amounted to 10,800 grams per square centimetre of section. But from this point onwards *the magnetising current and the weight that could be carried increased in exactly the same proportion.* The rate of increase of the load was, indeed, comparatively small, but it was perfectly constant, and continued so until the field had attained the high intensity of 1074 C.G.S. units. Here the experiment was stopped, the greatest weight supported having been 15,100 grams per square centimetre.

On account of some uncertainty as to the possible influence of the external ends of the divided rod, it was thought desirable to make the experiment with the divided ring, the current being caused to pass in the same direction through the coils surrounding both portions. The general character of the results was the same as before, but the weight

supported per unit of area was from first to last somewhat greater. The falling off in the rate of increase of the lifting power was well marked when the intensity of the magnetic force had reached 50 C.G.S. units, at which point the weight sustained was about 10,000 grams per square centimetre. And it continued to diminish until the magnetic force was 250 units and the weight supported 14,000 grams. From this point the increments of lifting power and of magnetic force appeared to be exactly proportional, and continued to be so until the magnetic force had been carried up to 585 units, when the limit of the battery power was reached and the experiment stopped, the maximum weight supported having been 15·905 grams per square centimetre or 229·3 lb. per square inch.

Detailed results of the experiment with the divided ring are given in the first and second columns of the Table. A curve plotted with the magnetic forces as abscissæ and the weights lifted as ordinates, becomes sensibly a straight line inclined to the horizontal axis for the values of the magnetic force greater than 240 units.

It occurred to the author that these results might be applied to the investigation of the changes of magnetisation which correspond to changes of magnetic force. The common belief that at a comparatively early stage the intensity of magnetisation becomes sensibly constant is, he imagines, founded rather upon inference than upon actual observation. At all events, he is acquainted with no experiments bearing upon the subject which have been made with magnetic forces at all comparable in magnitude with those used by himself.

If W = the grams weight supported per square cm. of section, H = the magnetic force and I = the magnetisation, we have

$$Wg = 2\pi \mathsf{I}^2 + \mathsf{H}\,\mathsf{I}$$

and by giving to W the values found by experiment to cor-

respond with different values of H we have the means of finding corresponding values of H and I. These are given in the first and third columns of the Table. Here, again, it will be seen that when H has exceeded the value of about 200 the ratio of I to H no longer continues to diminish, and the curve expressing the relation between them apparently becomes a straight line.

It is not suggested that the portions of both the curves for W and H, and for I and H, which, so far as the experiment goes, differ insensibly from straight lines, would, in fact, continue to appear as absolutely straight if they were prolonged indefinitely. It is indeed probable that at least one of them tends to a limit. But the experimental results give no indication of the existence of any such limit, and if there is one it must be considerably higher than it is generally believed to be.

If κ denote the susceptibility, μ the permeability, and B the magnetic induction—

$$I = \kappa H$$

$$\mu = 1 + 4\pi\kappa$$

and

$$B = \mu H$$

We can, therefore, easily find the values of κ, μ, and B, which correspond to different values of H. These are given in the fourth, fifth, and sixth columns of the Table.

In connection with the well-known experiments and views of Prof. Rowland, the figures thus obtained are of the highest interest. In order to exhibit the results of his experiments in the form of a curve, which (as he believed) would be of finite dimensions, Rowland adopted the method of plotting the value of μ as ordinates against those of B as abscissæ. The curve of μ thus obtained, after reaching a maximum for a moderate value of B (about 5000) fell very rapidly, and ultimately, to all appearance, in a perfectly straight line towards the horizontal axis, which, however, was not quite reached within the limit of his experiments.

Rowland, therefore, assumed that the line would continue to be straight until it met the axis at a point the abscissæ of which would indicate the greatest possible value of B. He thus arrived at the conclusion that for ordinary bar iron the maximum of magnetic induction was about 17,500 units. For pure iron he thought it might reach 18,000, or even go above that. (For Rowland's curve, see p. 14, Fig. 7.)

Now, the magnetic force used in Rowland's experiments was very small, the highest value being only 64 C.G.S. units. The imaginary part of his curve, therefore, corresponds to values of H ranging from 64 to infinity. A part of this exceedingly wide gap is filled by the author's experiments, which include values of H up to 585, and a curve constructed from the values of μ and B in the fifth and sixth columns of the table seems to throw much new light on the subject. It corresponds, of course, only with a portion of Rowland's curve, the lowest value of B included in it being only 7390. Beginning with a rapid descent, it turns aside soon after the limit of Rowland's observations has been passed, and ultimately, when B = 19,800, it has become almost parallel to the horizontal axis. We may conclude, then, that if B has any ultimate limit at all, it is, at all events, very much higher than that which was assigned to it by Rowland.

There may perhaps be some doubt whether the expression used to connect W and I is exactly applicable to the case of the divided ring, and small errors may possibly be introduced by the fact that the contact between the opposite faces was not quite perfect throughout. But apart from minute accuracy of detail, the general character of the results is entirely free from doubt, and would be quite unaffected by a very large margin of uncertainty in the expression. They show that the generally-accepted ideas with regard to several important points need modification.

Thus it is not true that the lifting power of an electromagnet reached a practical limit under a comparatively

small magnetising force, and that even if excited by an infinite current it could not support a weight of 200 lb. per square inch of surface.

It is not true that the magnetisation of iron becomes sensibly constant when the magnetic force exceeds a certain moderate value.

And it is not true that the maximum of magnetic induction, if it exists at all, is represented by anything like so small a value as 18,000 units.

In conclusion, the author has to express his great obligation to Lord Rayleigh for much valuable assistance and advice in the preparation of his paper.

TABLE.

H = magnetic force.
I = magnetisation.
κ = susceptibility.
W = weight in grms. per sq. cm.
B = magnetic induction.
μ = permeability.

H	W	I	κ	μ	B
3·9	2210	587	151·0	1899·1	7390
5·7	3460	735	128·9	1621·3	9240
10·3	5400	918	89·1	1121·4	11550
17·7	7530	1083	61·2	770·2	13630
22·2	8440	1147	51·7	650·9	14450
30·2	9215	1197	39·7	500·0	15100
40	9680	1226	30·7	386·4	15460
78	11550	1337	17·1	216·5	16880
115	12170	1370	11·9	150·7	17330
145	12800	1403	9·7	122·6	17770
208	13810	1452	7·0	88·8	18470
293	14350	1474	5·0	64·2	18820
362	14740	1489	4·1	52·7	19080
427	15130	1504	3·5	45·3	19330
465	15275	1508	3·2	41·8	19470
503	15365	1510	3·0	38·7	19480
557	15600	1517	2·7	35·2	19630
585	15905	1530	2·6	33·9	19820

We may refer the student also to two very important papers published in the 'Philosophical Transactions' of the Royal Society, Part II., 1885: one by Dr. John Hopkinson on the 'Magnetisation of Iron,' and the other by Professor J. A. Ewing, entitled 'Experimental Researches in Magnetism.' These papers, which are most exhaustive in treatment, will provide the advanced student with the most recent information on the subject of the magnetisation of iron and steel.

An abstract of some of Professor Ewing's latest work will be found in 'Industries' for September 30, 1887, p. 377; in which is described the *isthmus* method of experimenting. By concentrating lines of force through a very narrow isthmus of iron connecting two massive pole pieces, Professor Ewing has been able to force up the induction through iron to 45,350 lines per square centimetre, the magnetising force being about 25,000 units. Experiment seems to indicate that there is no defined limit to the magnetisation of iron, although the permeability becomes very small, and continually approximates to unity.

APPENDIX II.

On the Manufacture of Clark's Standard Cells.

As the value of Clark's standard cells entirely depends on the certitude with which independent manufacturers can by their use recover a unit of electromotive force for themselves, it may not be superfluous to supplement the remarks in the text by a few further suggestions on the precautions to be taken in order to secure the best results. The mercury having been carefully twice distilled in vacuo, the next step is the preparation of a saturated solution of zinc sulphate. The purest possible crystallised zinc sulphate is dissolved in water, about two parts by weight of the crystals to one of water. A little carbonate of zinc and some mercurous sulphate is added to neutralise free acid, and the solution is effected by the aid of gentle heat. The solution will generally deposit after a time a brown flocculent precipitate which is iron, and should be filtered off through a warm filter. The crystals should be present slightly in excess, so as to secure perfect saturation of the solution, and in taking off the solution for use from the bottle a pipette should be used, and the solution extracted from the bottle from just above the crystals. A paste is then prepared, by mixing in a mortar thirty parts of mercurous sulphate, one part of zinc carbonate, and as much of the zinc-sulphate solution as will form a thick paste. This paste generally turns a canary yellow, and froths up a good deal. It should be left a few days, and stirred up at intervals until all frothing

has ceased. Add a few crystals of zinc sulphate, and transfer the paste to a stoppered bottle for use. This paste is then poured out on to the mercury in making up these cells as described. Difficulty sometimes occurs from the gradual "creeping" up of the salts around the stopper. It is not a good plan to seal the cells with paraffin, because this never really adheres to the glass. The rubber stoppers, if made warm and smeared with hot melted marine glue, make a good joint with the glass when pushed into their place.

The great point to be attended to in manufacture, next to the perfect purity of the mercury and the zinc, is to secure that the zinc-sulphate solution shall be saturated (but not supersaturated) at the highest temperature at which the cells will be used. Generally speaking, even when made up with all care, the E.M.F. of the cell is a little too high at first, and it is only after a week or two of rest that the cell arrives at its proper electromotive force.

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